CIWRO

FIVE-YEAR SCIENCE REVIEW BRIEFING BOOK
OCTOBER 2021 – MARCH 2025

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UNIVERSITY OF OKLAHOMA
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Cover photo: Lightning strikes during a thunderstorm in Newcastle, Oklahoma, during the PAPEL field campaign on June 15, 2023, in which CIWRO was a participant. Photo by Michael Stock, CIWRO Research Scientist.

EXECUTIVE SUMMARY

The Cooperative Institute for Severe and High-impact Weather Research and Operations (CIWRO), established in 2021, extends cooperative agreements between NOAA and the University of Oklahoma (OU) that have existed continuously since 1978. Starting in 2021, CIWRO became a consortium with partners at the University at Albany, Howard University, Penn State University and Texas Tech University. CIWRO is collocated with several NOAA research labs (the National Severe Storms Laboratory NSSL, the Storm Prediction Center SPC and the Warning Decision Training Division WDTD) at the National Weather Center (NWC) in Norman, Oklahoma and is the largest research center at OU employing 227 researchers, support personnel and students.

CIWRO's vision is to be a global leader in severe and high-impact weather research, bridging partnerships between OU, NOAA, and consortium institutions to transform scientific understanding into products that provide innovative, life-saving forecasts that reduce the impacts of extreme weather on communities and ecosystems. CIWRO's mission is to foster collaborative research between CIWRO scientists and NOAA partners on issues of shared interest, aiming to enhance the understanding of weather phenomena. By transitioning research findings into operational products, CIWRO seeks to improve weather forecasts and warnings, ultimately saving lives, protecting property, and reducing the economic impacts of storms. The research at CIWRO focuses on advancing fundamental knowledge of weather radar, multi-scale processes, and subseasonal to seasonal predictions. The transition of products to operations supports faster, more accurate, and valuable weather and water information, guiding decision-making to minimize loss of life, injury, and economic damage. Critical to CIWRO's success are the integration of improved observations, modeling, data assimilation (DA), and the study of social and socioeconomic impacts of high-impact weather. Both research-to-operations (R2O) and operations-to-research (O2R) processes play a key role in driving this mission. CIWRO's scientific mission is carried out through five key research themes: 1) Weather radar and observational R&D, 2) Mesoscale and storm-scale modeling R&D, 3) Forecast applications improvements R&D, 4) Subseasonal to seasonal (S2S) prediction for extreme weather events, and 5) Social and socioeconomic impacts of high-impact weather systems.

Highlights of CIWRO accomplishments since its formation on 1 October 2021 include the following: 353 published papers (1,704 since 1978); 837 presentations at conferences, workshops and at partner institutes; 55 research products transitioned into operations; generation of 58 data sets; quality control of over 17 Terabytes of data; conduct of 58 testbed evaluations; production of more than 1.3M lines of software for the Advanced Technology Demonstrator; 4,160,000 reports to the mPING system; publication of at least 806 papers all-time using data from the Multi Radar Multi Sensor (MRMS) product or using the Warn on Forecast System (WoFS); MRMS is a key system that has now been operational for 10 years at at the National Weather Serice (NWS) and is relied upon by many; employment of 47 graduate and 130 undergraduate students during CIWRO's lifetime; awarding of 49 external non-Task III proposals for a total of $42,960,985 in funding; transition of 59 CI-supported students/postdocs/research scientists/associates to employment in positions related to the fulfillment of NOAA's objectives; and consumption of a minimum of 81,943 hours of CI-pro-

Photo 0-1: An EF2 tornado touches down in Morton, Texas, on May 23, 2022, during the TORUS field campaign. Photo by CIWRO Graduate Research Assistant Angela Mose.

duced training by NWS Forecasters. Recognition of CIWRO's work is widespread. In 2024, WoFS was awarded the NOAA Department of Commerce Gold Medal in recognition of nearly 2 decades of research and development of the WoFS system. Forty-three students and post-doctoral fellows have won awards for the quality of their presentations at national and international conferences.

Education, outreach, and training are vital components of CIWRO's efforts, building capacity to support NOAA's future research and operational activities. A major educational component includes several OU and consortium faculty and staff advising and mentoring graduate and undergraduate students in funded positions, capstone projects, Hollings projects, a Research Experience for Undergraduate (REU) program, funding for the prestigious Peter Lamb Postdoctoral Fellowship, travel opportunities for students to field campaigns and conferences, summer research colloquia, and active participation in various student clubs. The vibrant outreach program involves classroom visits to K-12 schools, the creation and loaning out of travelling trunks (pre-assembled comprehensive lesson plans with supplies) on clouds and tornadoes to K-6 schools, development of curriculum on "Weathering the Storm" by the Tulsa Regional STEM Alliance, (a middle-school career elective exploratory course), teacher workshops entitled "Twisted: Unraveling the Science of Severe Weather for Teachers of Grades 3-6", visits to summer camps and after school programs such as "Five Nights of Eddies: Surviving Tornadoes, Hurricanes and Other Severe Weather", participation in fairs and festivals, and operationally based warning and forecast exercises for high school students based on simulations provided by WDTD.

CONTENTS

ABOUT CIWRO

The Cooperative Institute for Severe and High-impact Weather Research and Operations (CIWRO) was established in 2021 and extends cooperative agreements between NOAA and the University of Oklahoma (OU) that have existed continuously since 1978. CIWRO connects the scientific and technical resources of OU, and consortium partners, and NOAA with the goal of improving the basic understanding of weather and transitioning that understanding to operations to produce better forecasts that save lives and property and minimize the economic damage associated with severe and high-impact weather. CIWRO is headquartered at the National Weather Center (NWC) in Norman, Oklahoma and is the largest research center at OU employing 227 researchers, support personnel and students. In 2021, CIWRO became a consortium with partners at the University at Albany, Howard University, Penn State University and Texas Tech University.

CIWRO is a continuation of the first NOAA Cooperative Institute at OU: the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS). The history of CIMMS/CIWRO is illustrated in Figure 0.1. Rex Inman started the idea of a Cooperative Institute at OU in 1975, and, in 1978, the institute was created through an OU and NOAA cooperative agreement. During the early years, CIMMS worked within shared space in OU's former engineering laboratory building. The organization set a precedent of research upon being founded and was one of the first research groups in Meteorology at OU. The cooperative agreement set up a new collaboration with the NOAA National Severe Storms Laboratory (NSSL) during this time, and Inman served as director from 1978 to 1980.

In 1980, Yoshi Sasaki became the director of CIMMS. Sasaki was instrumental in developing OU's meteorology program and strengthening the ties with the institute's federal partners and international organizations. Strengthening partnerships with both the university and the NSSL was Sasaki's legacy. He assisted in creating an agreement between OU and Kyoto University in Japan, promoted research and relations between the United States and Japan, and he worked on an international consortium of universities, government and private enterprise to alleviate the loss of life and property. His dream was to see universities, private businesses and government unite to lessen the devastating effects of natural disasters. Sasaki served as CIMMS director from 1980 until 1986.

In 1986, Doug Lilly became CIMMS' director. CIMMS moved into the Sarkeys Energy Center on OU's campus during this time and Lilly served as director of CIMMS while steer-heading efforts for the development of the Center for the Analysis and Prediction of Storms (CAPS). In 1991, he left his position at CIMMS to work with CAPS full-time. CIWRO and CAPS still enjoy a collaborative partnership.

In 1990, researchers within NSSL and CIMMS began development of the Warning Decision Support System (WDSS). WDSS was designed to enhance NWS capabilities, and included a new set of algorithms for tornado, hail, mesocyclone, microburst, and storm cell detection and tracking. It also included a unique display capability that could quickly analyze data from a single radar using this algorithm information, such as time-height trends of various radar data fields. CIMMS and NSSL personnel traveled around the country, conducting months-long tests at geographically diverse NWS Forecast Offices, to work directly with forecasters

Photo 0-2: Experimental products developed by CIWRO researchers are evaluated by NWS forecasters in the NOAA HWT: Satellite Convective Applications Experiment in 2024. Researchers and forecasters work together to improve the detection and prediction of severe weather hazards, such as tornadoes and large hail. The focus of this experiment was to evaluate the products and capabilities of the satellites in a real-time environment and allow experiment participants to provide constructive feedback. Photo courtesy NOAA NSSL.

on improvements to the algorithms. WDSS was replaced by a system that became the core of the Multi-Radar Multi-Sensor System (MRMS) that is used today. Further, many of the WDSS algorithms and display features were transitioned to the operational WSR-88D and AWIPS Systems.

Peter Lamb joined CIMMS in 1991 and became the organization's longest-serving director to date, serving as director until his passing in 2014. At the beginning of Lamb's tenure, he successfully competed for the Site Scientist Program for the developing the Southern Great Plains Cloud Radiation Testbed in northern Oklahoma - one of three worldwide sites at the time in the Atmospheric Radiation Measurement program sponsored by the U.S. Department of Energy; this site is still active today. In 1994, CIMMS researchers participated in the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX) with NSSL. VORTEX was originally a two-year project designed to answer several ongoing questions about the causes of tornado formation; variations of the VORTEX project continue to this day. Additionally, during 1991, CIMMS began a partnership with the NOAA NWS Storm Prediction Center and this relationship continues today.

In 1995, the Department of Commerce awarded NSSL and its partner cooperative institute a gold medal for work leading up to, and the ongoing support, of the national deployment of the Doppler WSR-88D radars. In 1997, NSSL received permission to upgrade its WSR-88D radar prototype with dual-polarization technology, and CIMMS researchers were instrumental in helping develop such technology. The prototype determined the practicality of upgrading the nationwide network of Doppler radars.

In 1996, CIMMS researchers began working and collaborating with the NWS Operations Training Branch (OTB). Today, OTB is the NOAA NWS Warning Decision Training Division

History of CIWRO

1978

First steps

CIMMS officially created through an OU and NOAA cooperative agreement; Rex Inman is initial director

1980

Creating partners

Yoshi Sasaki became the director of CIMMS, strengthened ties with NSSL & Kyoto University

1981

New leadership

Peter Lamb became director of CIMMS

1986

Prediction trailblazer

Doug Lilly became CIMMS director and CIMMS moved into the Sarkeys Energy Center on OU. He steered efforts to create Center for the Analysis and Prediction of Storms

1990

Forecaster training

NSSL/CIMMS researchers began development of Warning Decision Support System (WDSS)

1992

Testbed awarded

CIMMS was competitively awarded the Site Scientist of Southern Great Plains Cloud (SGP) Radiation Testbed

1994

VORTEX participant

CIMMS participates in Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX); CIMMS begins partnership with SPC

1995

Gold Medal for radar

NSSL and partner CIMMS receive Gold Medal for work relating to national deployment of Doppler WSR-88D radars

1996

WDTD collaboration

CIMMS begins collaborating with NWC Operations Training Branch (OTB), now NOAA NWS Warning Decision Training Division (WDTD); WDSS plays key role in supporting operations at Olympic Games

1997

Radar tech upgrade

CIMMS researchers instrumental in upgrade of WSR-88D radar prototype with dual-polarization technology

2000

ARM Addition

ARM Data Quality Office awarded to CIMMS

2003

OKLMA & PAR advancements

Oklahoma Lightning Mapping Array (OKLMA) initiated and important for CIMMS investigations; phased array radar (PAR) added to NOAA's National Weather Radar Testbed (NWRT) and used for research

Figure 0.1: Schematic showing timeline of CIWRO's history

2005

Leaders in SHAVE

CIMMS researchers led Severe Hazards Analysis and Verification Experiment (SHAVE)

2006

New headquarters

CIMMS moved to its current home at National Weather Center

2009

VORTEX2 launches

NSSL collaborates with CIMMS on the VORTEX2 project, largest field tornado research project in history

2010

Kansas City expansion

CIMMS/NSSL won the prestigious Vaisala Award for their outstanding PAR research paper; CIMMS researchers began working at National Weather Service Training Center in Kansas City, Missouri

2011

Institute renewal

CIMMS successfully competed to continue 5 more years of operation by new competitive process within NOAA

2012

mPING introduced

Meteorological Phenomena Identification Near the Ground (mPING) mobile app launched

2014

Silver Medal for MRMS

CIMMS director Peter Lamb passed away and Randy Peppler becomes interim director; NSSL and CIMMS win prestigious Silver Medal Award for MRMS deployment

2016

VORTEX-SE begins

VORTEX-SE began; CIMMS partnership with researchers at NOAA Air Resources Laboratory Atmospheric Turbulence and Diffusion Division in Tennessee began

2017

Current leadership

Greg McFarquhar was appointed director of CIMMS

2018

ATD installed

Advanced Technology Demonstrator installed at NWRT

2020

HWT goes virtual

Hazardous Weather Testbed (HWT) successfully operated in virtual mode due to pandemic

2021

CIMMS becomes CIWRO

OU successfully competed for new CI, Cooperative Institute for Severe and High-Impact Weather Research and Operations (CIWRO)

2024

Gold Medal for WoFS

CIMMS/NSSL researchers win U.S. Department of Commerce Gold Medal for Warn on Forecast System (WoFS)

(WDTD) and CIWRO continues to have a large workforce supporting WDTD. One of the first projects CIMMS researchers worked on for OTB was devising a way to quickly archive all available data sets after a major storm event, including radar, satellite, and upper-air observations, and this data became a quick, after-the-fact radar training tool for NWS forecasters to learn and review.

In the 2000s, there was another flurry of activity at CIMMS. In 2000, the ARM Data Quality Office was awarded to CIMMS and presently continues within CIWRO. In 2003, the Oklahoma Lightning Mapping Array (OKLMA) became operational and is still used by NSSL and CIWRO researchers to investigate lightning characteristics. In 2003, CIMMS and NSSL employees collaborated using a repurposed U.S. Navy phased array radar (PAR) located in NOAA's National Weather Radar Testbed (NWRT) to demonstrate the unique capabilities that phased-array antennae can provide for improved weather observations, showing that one-minute, entire storm volume updates are beneficial in forecasters' ability to extend severe and tornado warning lead times. In 2006, CIMMS moved to its current home at the newly built NWC. And, in 2009-2010 CIMMS and NSSL researchers collaborated on the conduct of the Verification of the Origins of Rotation in Tornadoes Experiment 2 (VORTEX 2) project, the largest tornado research project in history deploying many mobile radars and other instrumented vehicles to understand the conditions by which supercell thunderstorms give rise to tornadoes.

Photo 0-3: CIWRO researchers and NWS meteorologitsts survey tornado damage in Cole, OK, one day after the April 19, 2023, EF3 tornado struck the town. CIWRO researchers work with NWS to learn more about tornado warning reception and protective actions by speaking with survivors, emergency managers, and first responders following select tornado events. The Tornado Tales app also allows tornado survivors to share their stories with researchers. Photo by CIWRO Researcher David Hogg.

In 2006, with the occupancy of the NWC by NSSL and OU scientists, the Hazardous Weather Testbed (HWT) facility was created as a physical space between the operations area of the SPC and the Norman Weather Forecast Office. The HWT is a space where researchers can test and refine new methodologies, algorithms, and technologies. Each year the HWT brings together researchers and those specializing in operations to evaluate the utility of new science, technology and products, and allows researchers to learn from forecasters' needs to formulate future research strategies. This emphasis on research to operations and operations to research ultimately improves National Weather Service forecasts and warnings. In 2020, the HWT operated for the first time in an entirely virtual mode due to constraints from the pandemic: CIWRO staff were able to convert all activities to an entirely virtual mode with only a few months preparations, allowing the continued success of the Spring Experiment. The HWT now operates in a hybrid mode.

Photo 0-4: CIWRO scientists challenge sixth-graders to a tornado quiz game at Piedmont Intermediate School in Piedmont, OK, on March 4, 2025. Outreach efforts include elementary, middle and high school classroom visits and summer camp visits, with an emphasis on schools that have not traditionally received visits from scientists. Photo by CIWRO Outreach Coordinator Annette Price.

Between 2009 and 2016, the Warn on Forecast System (WoFS) was conceived and built by scientists at CIMMS and NSSL. WoFS is designed to increase the lead time for tornadoes, severe thunderstorms and flash flood warnings. Since 2017 CIMMS/CIWRO and NSSL have formed a collaborative team to run WoFS and study its impact on real-world forecast applications. Recently WoFS has enabled forecasters for the first time to message probabilistic hazard information associated with individual severe storms between the watch-to-warning time frame. In 2024, WoFS was awarded the NOAA Department of Commerce Gold Medal in recognition of nearly 2 decades of research and development of the WoFS system.

The 2010s were an equally active period for CIMMS, with OU winning a national competition to renew operations of CIMMS for another 5 years (and subsequent renewal for another 5) via a new competitive process within NOAA. After Peter Lamb's passing, Randy Peppler served as interim director until 2017, when Greg McFarquhar became the new director and continues as director of CIWRO today. In 2010, CIMMS expanded collaborations when re-

searchers began working at the National Weather Service Training Center in Kansas City, Missouri. In 2016, the Verification of the Origins of Rotation in Tornadoes Experiment SE (VORTEX-SE) seeking to understand the formation, intensity, structure, and path of tornadoes in the southeastern United States was started. In 2016, CIMMS created a partnership with researchers at the NOAA Air Resources Laboratory Atmospheric Turbulence and Diffusion Division in Tennessee, a partnership which continues within CIWRO. In 2018, the Advanced Technology Demonstrator (ATD) was installed at the NOAA NWRT. The ATD is a modern, dual-polarization, active phased array radar that has enabled critical research and development on phased-array radar by both NSSL and CIWRO scientists.

In 2021, OU won the competition for a new Cooperative Institute (CI) named the Cooperative Institute for Severe and High-impact Weather Research and Operations, or CIWRO for short. Although the majority of CIWRO researchers are based at the NWC, CIWRO also has personnel in Missouri, Tennessee, Texas, and Colorado. Capacities and capabilities at OU are now complemented by those at the consortium partners at Howard University, Pennsylvania State University, Texas Tech University and the University at Albany. CIWRO scientists perform research and transition research products into operations in five different themes (Figure 0.2):

1. Weather radar and observations research and development;
2. Mesoscale and stormscale modeling research and development;
3. Forecast applications improvement research and development;
4. Subseasonal to seasonal (S2S) prediction for extreme weather events; and
5. Social and socioeconomic impacts of high-impact weather systems.

CIWRO scientists are improving the observation, analysis and understanding of weather elements, S2S forecasts, and the forecast and warning decision-making processes through 1) enhanced knowledge of physical processes (mesoscale and stormscale dynamics, atmospheric electricity, cloud microphysics, planetary boundary layer processes), 2) development and application of observational tools (weather radar, profilers, mobile mesonet, lidars, field projects, Uncrewed Aircraft Systems (UASs)), 3) development and application of high-resolution numerical prediction models (including physical parameterizations, data assimilation systems, and ensemble systems) that include uncertainty estimates, 4) improved understanding of societal impacts of strategies for informing the public about high-impact weather, and 5) S2S predictions of the intensity and location of extreme weather. The transition of research products into operations and the use of artificial intelligence (AI) and machine learning (ML) are also critical.

CIWRO also encompasses a major education and outreach component that includes several CIWRO personnel and faculty at OU and consortium partners advising graduate and undergraduate students, the prestigious Peter Lamb Postdoctoral Fellowship, and a summer research experience for graduate students and undergraduates. CIWRO also offers ample opportunities for graduate and undergraduate students to conduct field research and to analyze results of data collected in the field, as well as attending major national and international conferences. CIWRO researchers also participate in many mentoring activities, including the Mentoring Ecosystems that have been developed by the School of Meteorology at OU, the Hollings Scholar program, and the National Science Foundation Research Experiences for

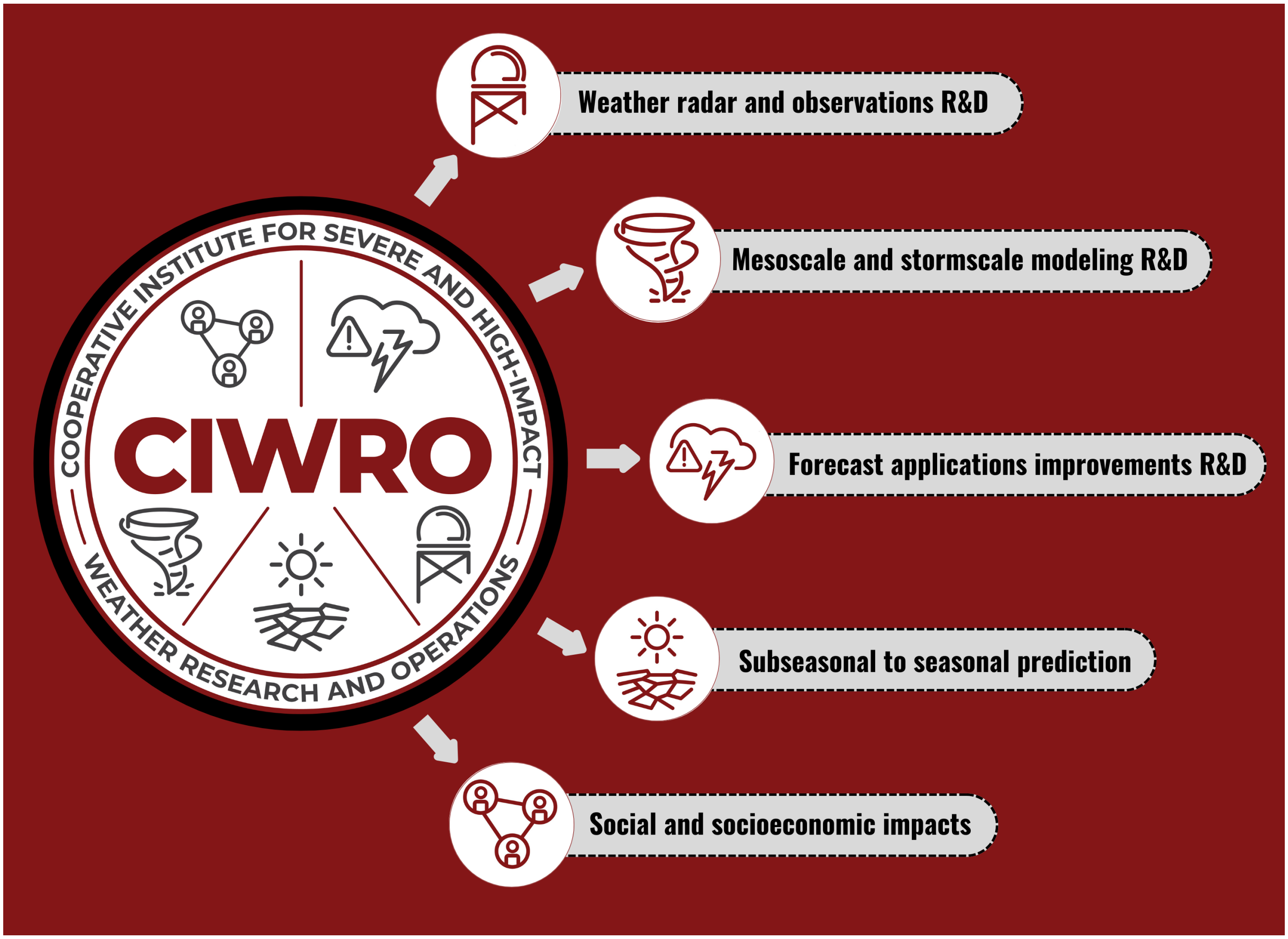


Figure 0-2. CIWRO's five research themes.

Undergraduates (REU) program conducted at OU each summer. CIWRO also has a major outreach program that reached more than 4,000 individuals in 2023 alone. Components of the outreach program include (1) elementary, middle and high school classroom visits and summer camp visits by CIWRO scientists, with an emphasis on schools that have not traditionally received visits from scientists; (2) teacher professional development events where teachers are provided with resources for teaching weather phenomena in the classroom; (3) development of travelling trunks which are comprehensive lesson kits with supplies for hands-on learning that ties science into other disciplines like reading and math, which each trunk highlighting different weather phenomena (trunks on clouds and tornadoes currently available); (4) collaboration with the Tulsa Regional STEM alliance on the development of curriculum for middle school students representing a stand-alone career exploration course and supplementary material for science classes; (5) participation in STEM community events, such as the Annual National Weather Festival at the NWC that attracts thousands of citizens; (6) holding of the “Five Nights of Eddies” STEM enrichment camp at the Boys & Girls Club of Norman that received the 2024 Education and Career Development Award; and (7) participation in career fairs at schools throughout Oklahoma.

1. SCIENCE PLAN

a. What is the scientific (not programmatic) vision for the institute?

The scientific vision of CIWRO is to be a global leader in severe and high-impact weather research, bridging partnerships between OU, NOAA, and consortium institutions to transform scientific understanding into products that provide innovative, life-saving forecasts that reduce the impacts of extreme weather on communities and ecosystems.

The mission of CIWRO is to foster collaborative research between CIWRO scientists and NOAA partners on issues of shared interest, aiming to enhance the understanding of weather phenomena. By transitioning research findings into operational products, CIWRO seeks to improve weather forecasts and warnings, ultimately saving lives, protecting property, and reducing the economic impacts of storms. The research at CIWRO focuses on advancing fundamental knowledge of weather radar, multi-scale processes, and subseasonal to seasonal predictions. The transition of products to operations supports faster, more accurate, and valuable weather and water information, guiding decision-making to minimize loss of life, injury, and economic damage. Critical to CIWRO's success are the integration of improved observations, modeling, data assimilation (DA), and the study of social and socioeconomic impacts of high-impact weather. Both research-to-operations (R2O) and operations-to-research (O2R) processes play a key role in driving this mission. Education, outreach, and training are vital components of CIWRO's efforts, building capacity to support NOAA's future research and operational activities. CIWRO's scientific mission is carried out through five key research themes: 1) Weather radar and observational R&D, 2) Mesoscale and storm-scale modeling R&D, 3) Forecast applications improvements R&D, 4) Subseasonal to seasonal (S2S) prediction for extreme weather events, and 5) Social and socioeconomic impacts of high-impact weather systems.

Research and transition to operations conducted in CIWRO falls in the five different themes listed above. CIWRO's work spans a broad range of topics including mesoscale and storm scale dynamics, atmospheric electricity, aerosol and cloud microphysics, and planetary boundary layer processes. The development and application of observational tools, such as weather radar, profilers, mobile mesonets, lidar, UAS, and piloted aircraft. The development and application of high-resolution numerical prediction models, including development and evaluation of associated physical parameterizations, data assimilation systems and ensemble systems that provide estimates of uncertainty associated with various outcomes is also an essential component of CIWRO's work. Finally, an improved understanding of societal impacts of different strategies for informing the public about imminent severe weather and high-impact events, and seasonal variation in weather extremes is also well within CIWRO's mission.

b. Does the CI have a Scientific Mission and/or Vision Statement?

Yes, CIWRO's scientific vision is listed in the first paragraph of Section 1.a., and its mission is summarized in the second paragraph of Section 1.a. Succinctly, CIWRO provides a mechanism to link the scientific and technical resources at OU and its consortium partners with those of NOAA to enable research that improves the observation, analysis, and prediction of weather elements and systems and weather anomalies ranging in size from cloud nuclei to synoptic (multi-state) areas. CWIRO is seeking to improve the understanding of weather phenomena and transition that understanding into operational products that will lead to better forecasts and warnings that save lives and property. This in turn contributes to improved social and economic welfare.

i. How were the scientific mission/vision developed?

The scientific mission and vision were developed in response to NOAA-OAPS-CI-PO-2021-2006682 that sought proposals for the establishment of a Cooperative Institute for Severe and High-Impact Weather Research and Operations (CIWRO). That funding opportunity sought a CI to conduct severe and high-impact weather research by improving NOAA's understanding of severe storms and established the five research themes listed in CIWRO's scientific mission statement. The request for proposal also encouraged the CI to include a wide range of supporting research affiliates, hence the establishment of consortium partners rather than just a single institute CI as CIMMS had been in the past. Collaboration with NOAA scientists is an essential component of the vision given that CIs are long-term collaborative partnerships between non-federal, non-profit research institutions and NOAA that promote research, education, training and outreach aligned with NOAA's mission as elucidated in the RFP.

ii. How are the science mission/vision communicated?

The scientific vision is listed on CIWRO's homepage available at https://www.ou.edu/ciwro. The mission statement is found at https://www.ou.edu/ciwro/about/vision-mission. The mission and vision of CIWRO are also communicated to employees at new employee orientations and repeated at all-hands meetings. In addition, the mission and vision of CIWRO are prominently featured on the CIWRO employee handbook that is available on the CIWRO website and distributed to all employees. Further, these goals are embodied in all the research we do, presentations we give, and the education and outreach that we engage in.

iii. How are the Vision and Mission related to the NOAA Strategic Plan in place at the time of adoption?

The vision and mission were adopted in 2021 when CIWRO was formed and were designed to help NOAA achieve objectives central to its mission of Science, Service and Stewardship (https://www.noaa.gov/our-mission-values-and-vision). CIWRO addresses two of the three foci within NOAA's mission statement, namely "to understand and predict changes in.... weather" and "to share that knowledge and information with others." NOAA's vision articulates that "the systematic study of the structure and behavior of the ocean, atmosphere and

related ecosystems" involves "integration of research and analysis, observations, … and modeling." Further, "NOAA science includes discoveries and ever new understanding of the ocean and atmosphere, and the application of this understanding to … the physical dynamics of high-impact weather events, the dynamics of complex ecosystems and biodiversity and the ability to model and predict the future states of these systems." NOAA's vision includes sharing that knowledge and information with others "for use by the nation's businesses, communities and people's daily lives." and includes "weather and water reports, forecasts and warnings …and the continuous delivery of a range of Earth observations and scientific data sets for use by public, private and academic sectors." At the time of the establishment of CIWRO, a component of NOAA's strategic plan had the long-term goal of Weather-Ready Nation that dictated that society be prepared for and respond to weather-related events to reduce loss of life, property and disruption from high-impact events. On the operational side, the NWS strategic plan in place at that time outlined a way to harness cutting-edge science, technology and engineering to provide the best observations, forecasts and warnings, including staying at the cutting edge of science, technology and engineering. For research and development (R&D), NOAA's Vision for 2020-2026 (NOAA 2020) included performing research and transitioning research products into operations to improve forecasts and warnings provided to the public. This included improving the fundamental knowledge of weather phenomena through observations and process-oriented understanding. CIWRO is making and has made measurable contributions in all of the above areas.

As a center of research excellence in severe and high-impact weather and related topics that fosters vibrant collaborations between NOAA and all the CIWRO consortium partners, the research performed at CIWRO has improved and is improving the fundamental understanding of weather radar and multi-scale processes affecting weather, has made and is making contributions to subseasonal to seasonal predictions, and is transitioning products to operations to allow improvements in forecasts and warnings that lead to better, quicker and more valuable weather and water information to support improved decisions that reduce loss of life, injury and damage to the economy. This is being done through improved observations, modeling, data assimilation (DA) and R2O/O2R. Of three R&D priority areas identified in NOAA's Vision for 2020-2026, two are within CIWRO's vision, namely reducing societal impacts from hazardous weather and other environmental phenomena; and a robust and effective research, development and transition enterprise.

Within these themes, CIWRO vision and mission is related to key questions listed in NOAA's Vision for 2020-2026 including:

- How can forecasts and warnings for hazardous weather and other environmental phenomena be improved (1.1)?
- How can NOAA enhance communications, products, and services to enable informed decision making (1.4)?
- How can unified modeling be integrated and improved with respect to skill, efficiency, and adaptability for service to stakeholders (3.1)?
- How can Earth observations be advanced to meet NOAA's needs (3.2)?

- How can information technology, Big Data, and AI be utilized to accelerate and transition R&D efforts and form new lines of business and economic growth (3.3)?
- How can NOAA ensure its investments are informed by focused social science research and application (3.4)?

c. What are the CI's goals and objectives within the Scientific Plan?

CIWRO's overarching goal is to improve the understanding of weather phenomena and transition that understanding into operational products that will lead to better forecasts and warnings that save lives and property. This is done by promoting collaborative research between OU and its consortium partners with NOAA on problems of mutual interest. Further, CIWRO aims to have a comprehensive education and outreach program in order to help educate and train the next generation of NOAA's and the nation's scientific workforce. Thus, the overarching objective of CIWRO is as follows:

- Promote collaborative research on the 5 CIWRO research themes between OU and its consortium partners with NOAA and other federal agencies with the goal of enhancing the understanding of weather phenomena and transitioning that training into operational products.
- Develop and implement a comprehensive education and outreach program for K-12 students, undergraduate students, graduate students, teachers, and the general public through a combination of classroom and after school visits, development of curriculum and teaching materials/tools, teacher workshops, career fairs, and community events, as well as providing opportunities for undergraduate and graduate students in research activities.
- Foster an environment where all staff can actively contribute to CIWRO activities while supporting their professional growth and development.

i. What criteria are used to measure progress in accomplishing these goals and objectives

In recognition of the need to establish metrics to evaluate the contributions CIs make to the NOAA mission as required by the Government Performance and Results Act, in 2018, the CI Directors collectively established metrics that are designed to evaluate CIs in a quantifiable and meaningful manner while providing some commonality between CIs (while recognizing that not all metrics apply to all CIs equally since there is a wide variety in the functions of CIs and their mechanisms for performing tasks). The metrics were designed to be as quantitative as possible, to measure the output of the CI or the outcome of the work performed by the CI. The metrics can be easily computed and should be accompanied by a narrative to fully understand the impact and breadth of a CI's accomplishments. From the list developed, the following metrics are used by CIWRO.

Science Dissemination

Number of papers in peer-reviewed journals per year. This information is included in the CI annual reports.

Number of non-referred reference documents (e.g., NOAA reports) *and conference presentations generated per year*. Ideally these documents should have a DOI to be easily traceable, but this is not always the case. This information is included in the CI annual reports.

Research Impact

Number of products transitioned into operations. This is the number of techniques, algorithms, instruments or products transitioned into operation by NOAA, another government agency or private company, and which are currently operational or ready for operational use pending approval from NOAA or another agency. However, because of the variable effort required to develop products (e.g., 1 major product can require more work than 20 minor products) and possible ambiguities on how the products are defined, a narrative describing the products must be included.

Leveraged Resources

Number of refereed papers based on data or models that were created with support from the CI by authors not belonging to or related to the CI. Double counting is avoided here by excluding papers authored by a CIWRO employee. An accompanying narrative should explain how the number is calculated and the significance of the impact.

Funding leveraging. The amount of funding from NOAA and other sources that supplements CI funding.

Career Development and Training

Number of PhD and MS degrees awarded to students supported by the CI.

Number of CI-supported students/postdocs/research scientists/research associates who have obtained employment in positions related to the fulfillment of NOAA's objective. A clear description of how it is determined that an individual is employed in a position related to NOAA's objective needs to accompany this number.

Amount of time CI-produced training is consumed both in person and on-line. This is accompanied by a description of how the training upon which the number is based.

d. What are the major scientific themes of the CI?

CIWRO researchers conduct work on the following five overarching themes:

1. weather radar and observations research and development;
2. mesoscale and storm-scale modeling research and development;
3. forecast applications improvements research and development;
4. subseasonal-to-seasonal (S2S) prediction for extreme weather events;
5. social and socioeconomic impacts of high-impact weather systems;

i. How were they identified and linked back to the themes NOAA used in the competition to create the CI?

The major science themes of CIWRO are identical to those that NOAA used in the competition to create the CI. Although the research being carried out in each of the thematic areas is steadily evolving, the themes themselves are not changing because they well encapsulate all the work that is being performed.

ii. What are the emerging thematic areas? Do these emerging themes arise directly from the existing CI themes, or are they based on changes since the CI was created?

All of CIWRO's current and emerging work is well encapsulated by the five existing themes. The emerging work in areas such as ML/AI, fire weather research and communication, and enhancing communication with emergency managers fits within existing themes.

iii. What are the drivers behind the emerging themes, and how does the CI fit them within the current science plan?

Emerging themes or areas of research are driven through both societal need and through identified needs of NOAA in order to better understand processes occurring in the atmosphere as needed to help produce better forecasts and warnings that save lives and property that minimize the economic damages caused by storms, to translate that understanding into the development of new and improved operational products, and to facilitate communication about these products to the general public, emergency managers, and the operational community. All emerging areas of research fit well within the existing themes: for any emerging topic area, we identify the theme(s) that the research fits best within.

e. Scientific Partnerships

i. What is your relationship to the NOAA Research Laboratories, Program Offices, Cooperative Science Centers and Other NOAA Entities (e.g., NMFS Science Centers)?

CIWRO has extensive collaborations with several NOAA Research Laboratories. Our largest partnership is with the NSSL and we have 121 employees and students working within NSSL. We also have 12 employees embedded within the SPC and 21 employees within WDTD, working on research projects, transitioning research into operations, developing and delivering training materials, and enhancing ways of communicating the results of our research. We also have an employee at the NWSTC in Kansas City, working on the planning and execution of operational readiness/experimental proof of concept evaluations, as well as employees embedded at the following NOAA offices: the Global Monitoring Lab in Boulder Colorado working on improving the prediction of related responses of land surface and boundary layer processes, and the NOAA Air Resources Laboratory in Oak Ridge Tennessee working on boundary layer processes and use of UAS technology. As Howard University is one of our consortium partners, we have a strong relationship with the NOAA Center for Atmospheric Sciences and Meteorology II (NCAS-M-II) through collaborative projects. Researchers from many of these institutes above have attended some of our workshops that have been conducted at either OU or the University at Albany.

ii. What, if any, formal procedures do you have for cooperative planning?

We regularly hold workshops where we invite attendance from our federal partners, other NOAA research laboratories, and other NOAA entities to engage in presentations and discussions that are designed to summarize state-of-art in a given topic area, what may be hindering research progress and transition of research products into operations in the topic area, determining the resources that are needed to overcome these impediments, and identifying work that should be pursued to overcome these hinderances. Since the creation of CIWRO, we have held such workshops in each of our five thematic topic areas: radar and observations research and development, mesoscale and storm-scale research and development, forecasts improvements research and development, S2S predictions for extreme weather events, and social and socioeconomic impacts of high-impact weather events. We also held workshops on the following specific topics: fire weather research and operations, fire weather integrated warning workshop, friends and partners aviation weather workshop, and workshop on science, predictability, operations and response to high-impact weather. We have plans for workshops in the fall of 2025 (workshop on landfalling hurricanes, use of AI/ML for science research, and outreach and education in severe and high-impact weather). As a result of these workshops, 1-page descriptions of potential future research directions are gathered and made available to workshop participants and federal partners as potential drivers of future research projects. Further, research proposals to targeted requests for proposals and unsolicited proposal opportunities that are synergistic with our funding from the Cooperative Agreement (e.g., to the National Science Foundation NSF) are generated from these workshops and help with cooperative planning and future research directions.

2. SCIENCE REVIEW

a. What are the Institute's most recent scientific highlights and accomplishments?

CIWRO scientists have made significant accomplishments in science and in translation of scientific research into operations as evidenced by the 353 publications completed or submitted since 1 October 2021, the 837 conference presentations, and the 55 products developed that are either in operation or ready to be transitioned to operations. These accomplishments are described in the five sections below, with accomplishments sorted according to the primary theme they were representing.

i. Weather Radar and Observations Research

CIWRO has made significant contributions to NOAA's mission through advancements in weather radar and observational research. Our research efforts contribute significantly to NOAA's objective of harnessing cutting-edge science and technology to improve observations, forecasts, and warnings. Our efforts focus on developing and using cutting-edge technologies, improving data quality, and enhancing forecasting and warning capabilities.

A key area of our work has been the continued improvement of the NEXRAD radar network. Through refinements in signal processing, radar echo classification, and polarimetric radar quantification of precipitation types, we have contributed to extending the operational capabilities of these systems. These improvements enhance the precision, timeliness, and accuracy of radar data, directly benefiting severe weather warnings and hydrological forecasts. CIWRO has also played a central role in the exploration of phased-array radar (PAR) as a potential next-generation weather radar system. Our research focuses on addressing engineering and meteorological challenges, including dual-polarization calibration, adaptive scanning strategies, and integration into operational forecast paradigms such as Warn-on-Forecast (WoF) and Probabilistic Hazard Information (PHI) through collaboration with operational forecasters. These efforts will support NOAA's decision-making process for future radar investments. Our work extends beyond traditional radar systems to include complementary observing techniques such as the integration of satellite data, ground-based sensors, and UAS. By synthesizing data from multiple sources, we have improved quantitative precipitation estimation (QPE) in complex terrain, enhanced the understanding of storm microphysics, and developed methodologies for radar-based nowcasting of severe weather. A key aspect of our efforts is the development and transfer of advanced radar technologies to operations. Notably, we have transferred a technique for range oversampling processing that has the potential to significantly enhance NEXRAD data precision. Furthermore, we are pioneering methodologies for dual-polarization radar data interpretation to improve forecasting of precipitation types, aviation safety in ice clouds, and microphysical parameterization in cloud models. CIWRO has led and contributed to field campaigns that provided unique observational datasets critical for advancing weather prediction models. These efforts included research on

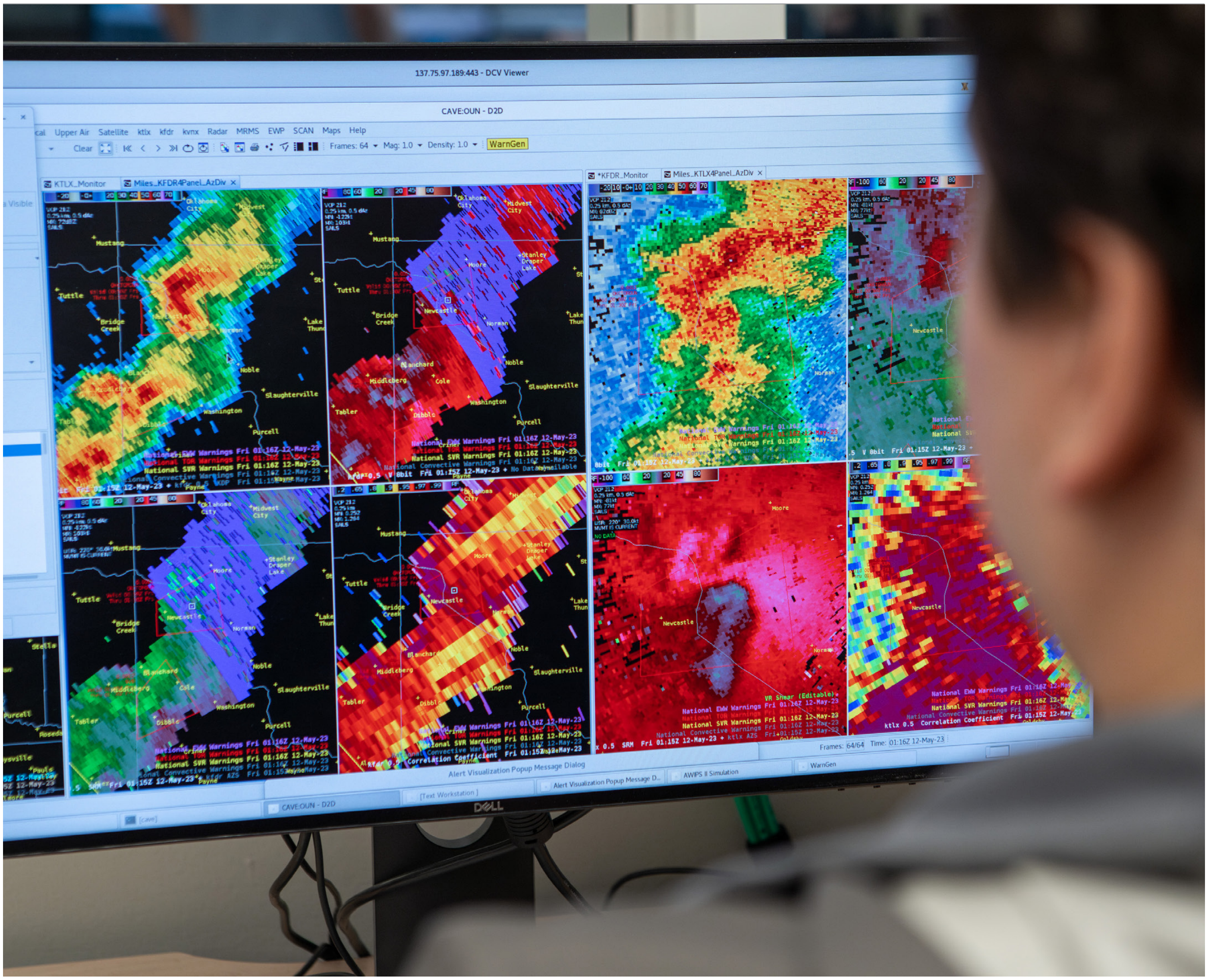


Photo 2-1: The Radar Convective Applications experiment provides an avenue for CIWRO researchers to obtain forecaster feedback for new applications and products developed for the WSR-88D network. This evaluation in 2024 focused on the Tornado Probability Algorithm (TORP), a machine learning single-radar product that detects and tracks potentially tornadic circulations, as well as the single-radar rotation and divergence products AzShear and DivShear to examine their effectiveness in predicting tornadoes and providing important situational awareness during severe weather operations. Photo by NOAA NSSL.

convective storm dynamics, winter precipitation processes, and atmospheric boundary layer characterization. Additionally, we have expanded the use of UAS technology for high-resolution atmospheric profiling and post-storm damage assessment, demonstrating its value in improving model representation and disaster response efforts.

CIWRO's research and development efforts in weather radar and observations are instrumental in advancing NOAA's mission. Our work ensures the continued evolution of critical weather observation technologies, ultimately leading to improved severe weather warnings, reduced societal impacts, and enhanced forecasting capabilities for the future.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Feng Nai, Sebastián Torres, David Warde
Project Title: Wind turbine clutter mitigation for weather radars
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

Wind turbine clutter (WTC) caused by rotating turbine blades is a growing challenge for weather radar systems like NEXRAD, introducing signal contamination that hinder accurate weather observations. Unlike stationary ground clutter, WTC is dynamic and influenced by turbine characteristics, requiring innovative mitigation strategies. This project developed and validated a practical signal processing solution for WTC mitigation, combining an automatic detection algorithm with a targeted filtering approach. The detection algorithm efficiently identifies WTC contamination, reducing computational demands by focusing on affected radar range bins, while the filtering algorithm removes WTC signals and preserves weather data. Proof-of-concept validation using NEXRAD data demonstrated the technique's effectiveness in recovering accurate weather signals. A machine-learning-based detection algorithm was also explored, leveraging spatial and spectral features for WTC identification, with performance demonstrated using multiple NEXRAD cases. Additionally, curated datasets of contaminated and uncontaminated radar data were created to train and validate detection algorithms. Collaborative work with the UK Met Office resulted in a convolutional neural network to mitigate WTC and stationary clutter for C-Band radars. Tangible outcomes include 5 conference presentations and contributions to 3 technical reports. This research advances the operational feasibility of WTC mitigation, addressing a critical challenge as wind energy expands across the U.S., and strengthens collaboration with international partners like the UK Met Office.

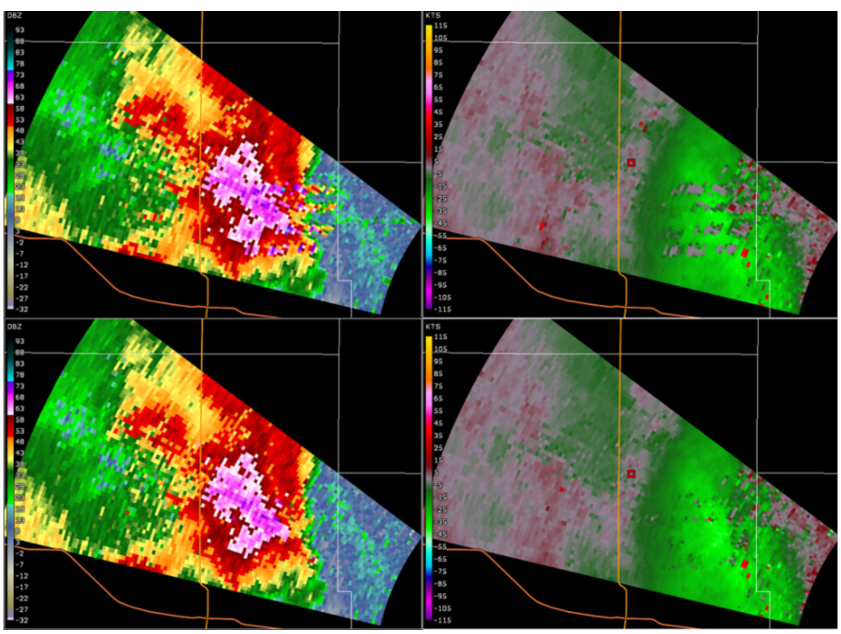


Figure 2-1: Unfiltered (top row) and filtered (bottom row) reflectivity and radial velocity for a case of WTC contamination collected by KDDC on 25 May 2020 at 02:26 UTC.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Sebastián Torres, David Warde
Project Title: Ground clutter mitigation for the NEXRAD network
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

Ground clutter, or radar signals reflected from stationary objects such as the ground and buildings, can distort weather radar data. To address these issues in the NEXRAD network, CIWRO developed two complementary algorithms: the Clutter Environment Analysis using Adaptive Processing (CLEAN-AP) and the Weather Environment Thresholding (WET). CLEAN-AP enhances clutter mitigation by more effectively removing stationary clutter while preserving weather signals, while WET uses dual-polarization radar data to differentiate weather signals from clutter, particularly in challenging near-zero-velocity scenarios. When combined, these algorithms significantly improve ground clutter suppression, leading to higher-quality radar data. Validation and verification efforts demonstrated the implementation of CLEAN-AP and WET on all NEXRAD transmission waveforms, including uniform pulse repetition time (PRT), pulse-to-pulse phase coding, and staggered PRT. Additional advancements included improved filtered correlation coefficient estimates and enhanced low signal-to-noise ratio (SNR) filtering based on correlation coefficient statistics. This work supported the NWS Radar Operations Center in evaluating and comparing clutter mitigation techniques across the network. Tangible outcomes include contributions to 3 technical reports and a significant enhancement to NEXRAD's signal processing capabilities. These developments are expected to improve radar-based weather monitoring and forecasting by providing more reliable weather-radar information. External collaborators included the NWS Radar Operations Center.

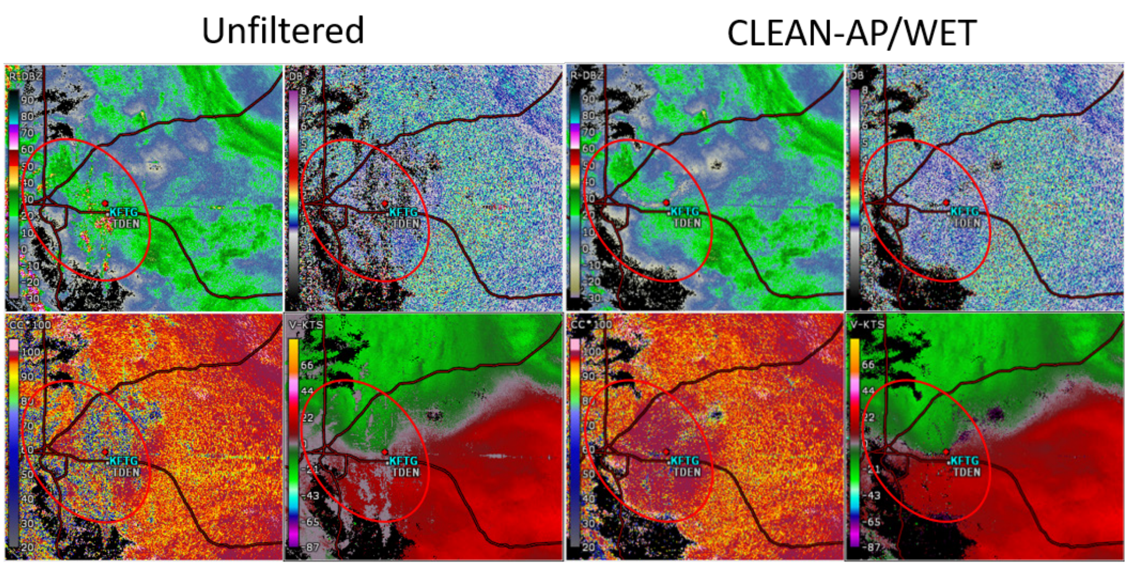


Figure 2-2: Comparisons of unfiltered (left four panels) reflectivity (upper left), differential reflectivity (upper right), correlation coefficient (bottom left) and velocity (bottom right) versus CLEAN-AP/WET ground clutter mitigation (right four panels). The red ovals correspond to areas where ground clutter is present in the left four panels and is mitigated in the right four panels using CLEAN-AP/WET.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Sebastián Torres, David Warde
Project Title: Range-and-velocity ambiguity mitigation for the NEXRAD network
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

Doppler weather radars are essential for observing and analyzing atmospheric phenomena but face challenges in balancing unambiguous range and velocity measurements, which is controlled by the pulse repetition time (PRT). Longer PRTs ensure complete range coverage, but they can cause velocity aliasing, while shorter PRTs resolve velocity ambiguities but lead to range folding, resulting in reduced data clarity. These range-and-velocity ambiguities may hinder accurate depiction of severe weather events like tornadoes. To address these limitations, recent advancements have combined two signal processing techniques: Staggered Pulse Repetition Time (SPRT) and SZ-2 phase coding. SPRT alternates PRTs to reduce velocity aliasing, and SZ-2 uses phase coding to mitigate range ambiguities. By combining these techniques, radar systems can optimize both range and velocity measurements, significantly improving the accuracy of radar data for storm tracking, precipitation estimation, and aviation safety. This project developed and recommended enhancements to the SZ-2 algorithm to address operational data quality concerns, assisted the NWS Radar Operations Center in resolving phase noise issues in the WSR-88D radar network, and designed scanning strategies using SPRT at mid-elevations. Tangible outcomes include 1 conference presentation and contributions to 3 technical reports.

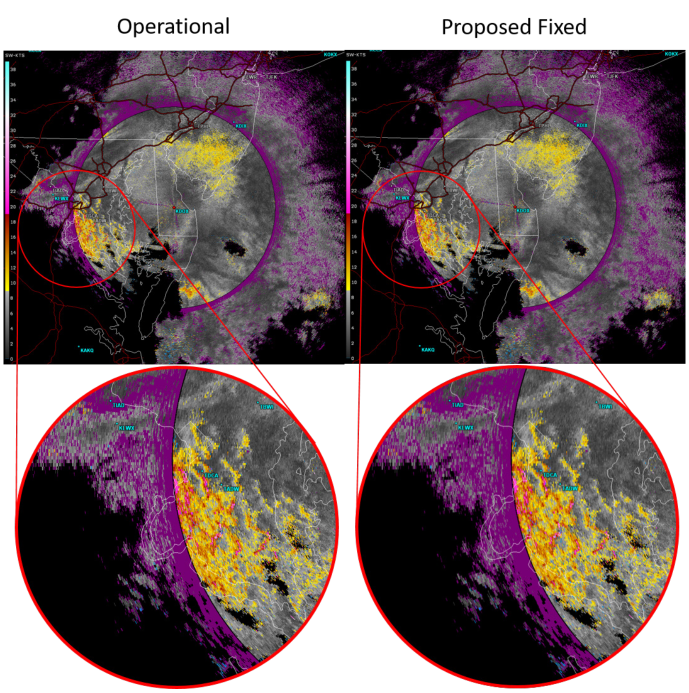


Figure 2-3: Spectrum width estimates using operational and proposed censoring thresholds. Additional censoring of the (incorrect) low spectrum width values immediately beyond the maximum unambiguous range prevents data misinterpretation (right image).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Christopher Curtis, Igor Ivić, David Warde
Project Title: Improved radar-variable estimation for the NEXRAD network
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

This project aims to enhance the accuracy of radar data using dual-polarization technology. The focus is on improving radar measurements, especially in challenging conditions such as weak signals or limited data samples. Several new methods have been developed, including the Weighted Adaptive Range Averaging (WARA), which improves radar data for distant areas; the Hybrid Correlation Coefficient (HCC), which enhances accuracy in noisy conditions; the Generalized Multi-Lag Estimators (GMLE), which provide better measurements of certain data types; and the Hybrid Scan Estimators (HSE), which offer improved polarimetric estimates. These advancements aim to increase the quality of radar data. Key accomplishments include the development of WARA for improving reflectivity, velocity, differential reflectivity, and correlation coefficient at low-to-moderate signal-to-noise ratios (Ivić 2024a; Curtis et al. 2022; Curtis et al. 2023; Curtis et al. 2024), and the improvement of GMLE for spectrum-width (Warde et al. 2023) that includes a technique that corrects GMLE bias (Curtis et al. 2023; Curtis et al. 2024). Additionally, a weighted GMLE estimator for spectrum width and a new correlation coefficient estimator were developed, minimizing bias at low signal-to-noise ratios (Curtis 2022). The project also contributed to enhancing HSE for use with the Multiple Pulse Repetition Frequency (PRF) Dealiasing algorithm. Tangible outcomes include 2 journal papers, 2 conference papers, 1 technology transfer, and contributions to 3 technical reports.

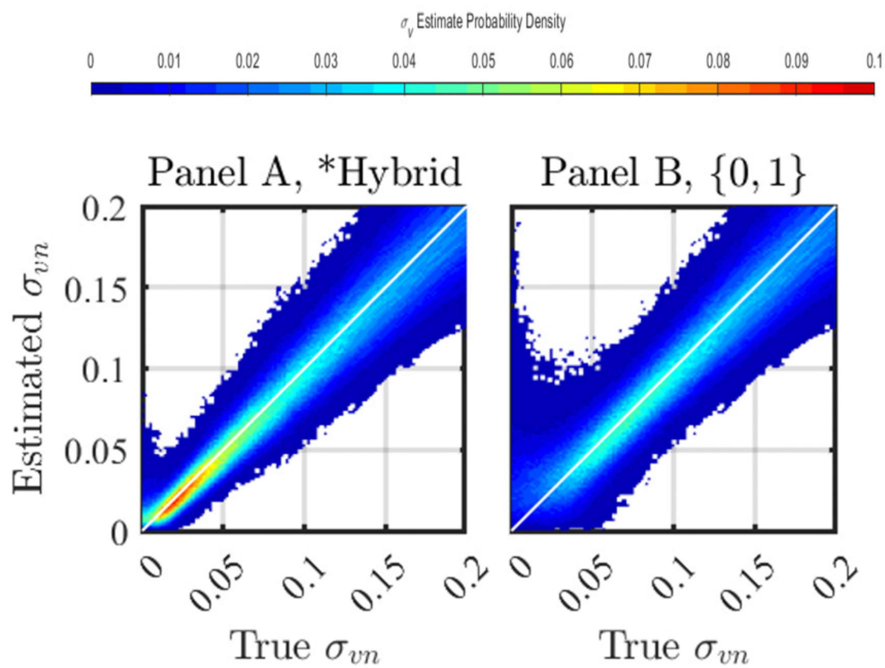


Figure 2-4: Panel A shows improved performance of the GMLE spectrum width as compared to the conventional estimator in Panel B.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Christopher Curtis
Project Title: Improved radar data quality control for the NEXRAD network
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

Quality control is essential for ensuring radar data is accurate and reliable, particularly when interference or clutter distorts the weather signals. Many existing techniques for managing data quality were developed before dual polarization was implemented on the NEXRAD network, and they have notable limitations. This project aims to improve radar performance by addressing radio frequency interference (RFI), a common issue that can contaminate radar signals. Specifically, the project evaluates a proposed RFI filter for integration into the NEXRAD network, with the goal of reducing interference and ensuring more accurate radar data for weather forecasting and analysis. Key accomplishments include providing critical information to the NWS Radar Operations Center to support the future implementation of the RFI filter to mitigate pulsed interference. Additionally, the project developed a new technique for detecting pulsed RFI using the phase of radar signals, which is expected to outperform conventional RFI detection methods in specific situations. This method could enhance radar signal quality in environments with high interference. Tangible outcomes from the project include 1 conference presentation and contributions to 3 technical reports.

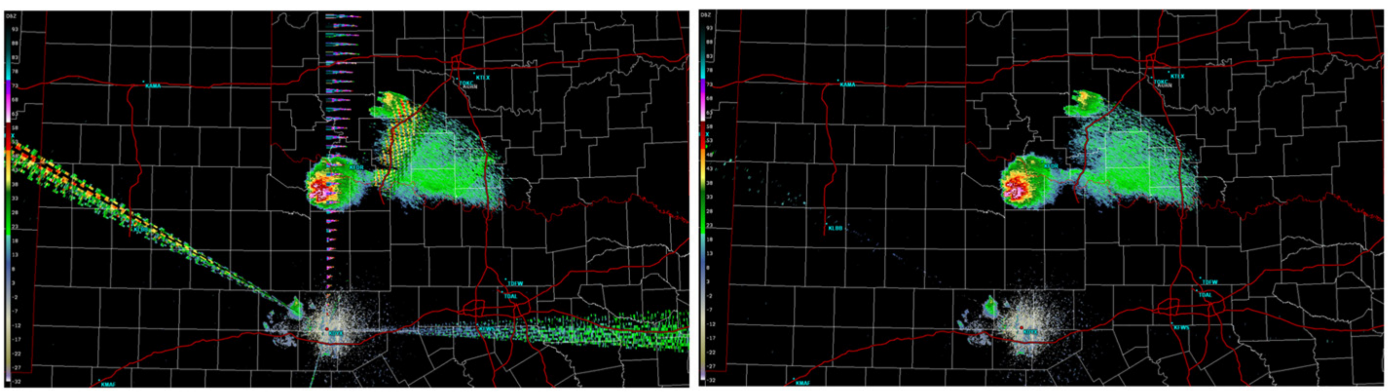


Figure 2-5: The left panel shows weather radar data contaminated with simulated pulsed interference, and the right panel shows the same data after processing with the new RFI filter.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Jami Boettcher, Yixin Wen, Erica Griffin, Feng Nai, Chis Curtis
Project Title: Interference simulations
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

Project Summary: As pressure on the S-band spectrum has grown and will continue to grow, this project was critical toward the establishment of interference protection criteria for the WSR-88D fleet. The work was performed for the NWS Radio Frequency Management Division (RFMD). Through simulations, different interference filtering levels were applied to WSR-88D cases with interference of differing types. The results were analyzed from impacts on the ability of an NWS forecaster to interpret the radar base data (reflectivity, velocity, spectrum width, differential reflectivity, correlation coefficient, and specific differential phase), and impacts on the results from two key algorithms: one that estimates accumulated rainfall, and a second that attempts to identify tornadic circulations. The base data are foundational for interrogation of all types of weather hazards, thus cases from the WSR-88D fleet were chosen for threats from severe convection to winter storms. Interference that is not filtered contaminates these data and disrupts forecaster interpretation. A 4-tier system of disruption levels was developed, assigned to simulation results with varying interference filtering applied to the data. The data were ingested with differing interference filtering into the rainfall and tornadic circulation algorithms to assess the impacts on algorithm performance. Of the two, interference had a greater impact on tornadic circulations, resulting in missed circulations and false alarms. An extensive Final Report was provided to the RFMD as guidance toward the development of appropriate interference protection criteria to protect the data quality of the WSR-88D and future NOAA radar systems.

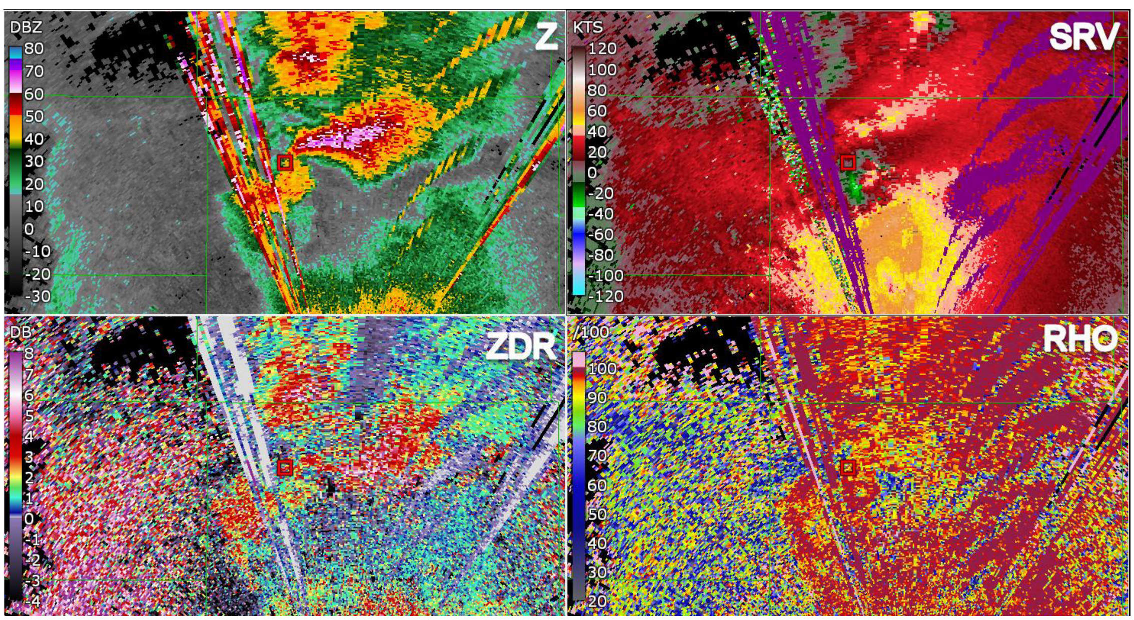


Figure 2-6: Example of two different types of interference causing major disruption for data interpretation of a tornadic supercell.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Christopher Curtis, Sebastián Torres
Project Title: Improved data precision using range oversampling for the NEXRAD network
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

This project addresses the challenges of observing rapidly changing weather events, such as tornadoes, using radar scans that update quickly but often sacrifice data quality or spatial resolution. To overcome this, an adaptive algorithm utilizing range oversampling was developed. Range oversampling collects additional data along each radar beam, enhancing the quality of radar measurements without increasing scan times. This technique enables faster updates while preserving the spatial coverage and precision necessary for accurate weather observations. Tests of the technique show a significant reduction in measurement variance, resulting in higher-quality data, particularly for polarimetric variables that require high precision to provide reliable insights into storm structure and intensity. The technique was successfully integrated with the hybrid correlation coefficient estimator, improving its performance (Curtis et al. 2022). A new simulation approach was also developed to reduce the time required for precomputing key adaptive algorithm parameters, significantly improving efficiency (Curtis 2023). These advancements were approved for integration into the NEXRAD network by the Technical Advisory Committee (TAC), paving the way for their use in real-time weather monitoring. Tangible outcomes include 1 conference presentation and contributions to 1 technical report, showcasing the effectiveness and potential impact of this approach on improving severe weather monitoring and analysis.

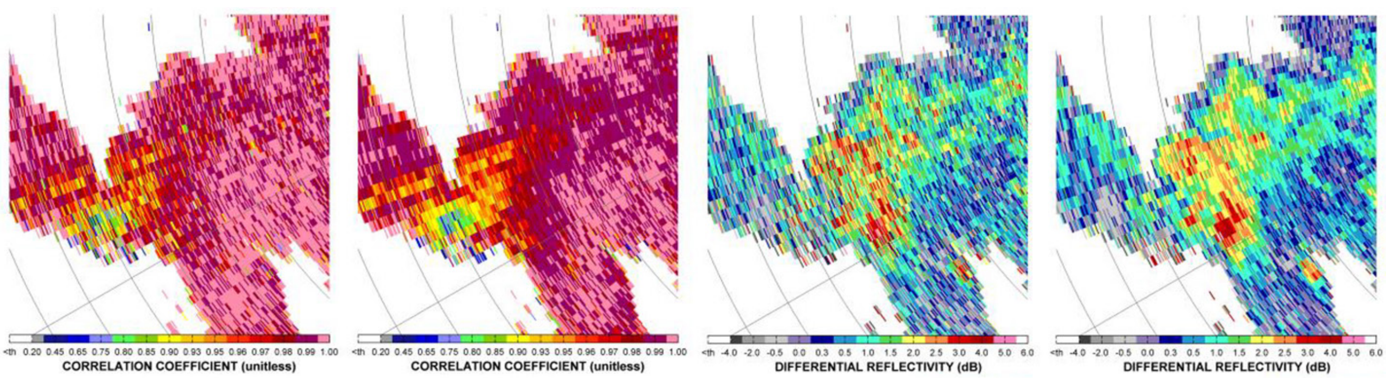


Figure 2-7: Fields of correlation coefficient (left two panels) and differential reflectivity (right two panels). For each pair of figures, the left panel was processed using conventional processing, and the right panel was processed using range-oversampling processing, resulting in data with better quality.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Lesya Borowska, Guifu. Zhang
Project Title: Classifying polarimetric radar returns using statistical approaches and including new variables
Relevance to NOAA: This project supports the NOAA mission to better utilize WSR-88D polarimetric radar data to improve hydrometeor classification

The hydrometeor classification improves the quantitative precipitation estimation and forecast. Polarimetric data from WSR-88D radars were analyzed. The figure shows an example of the field of the circular depolarization ratio (in dB) and its histogram. A fully-connected neural network algorithm is used to separate rain, rain/hail, birds, and insects with the polarimetric radar variables and their textures as inputs. The accuracy of the classifications is evaluated from the statistics of the differences between predicted and existing classes. It is shown that machine learning has potential application in improving weather radar echo classification.

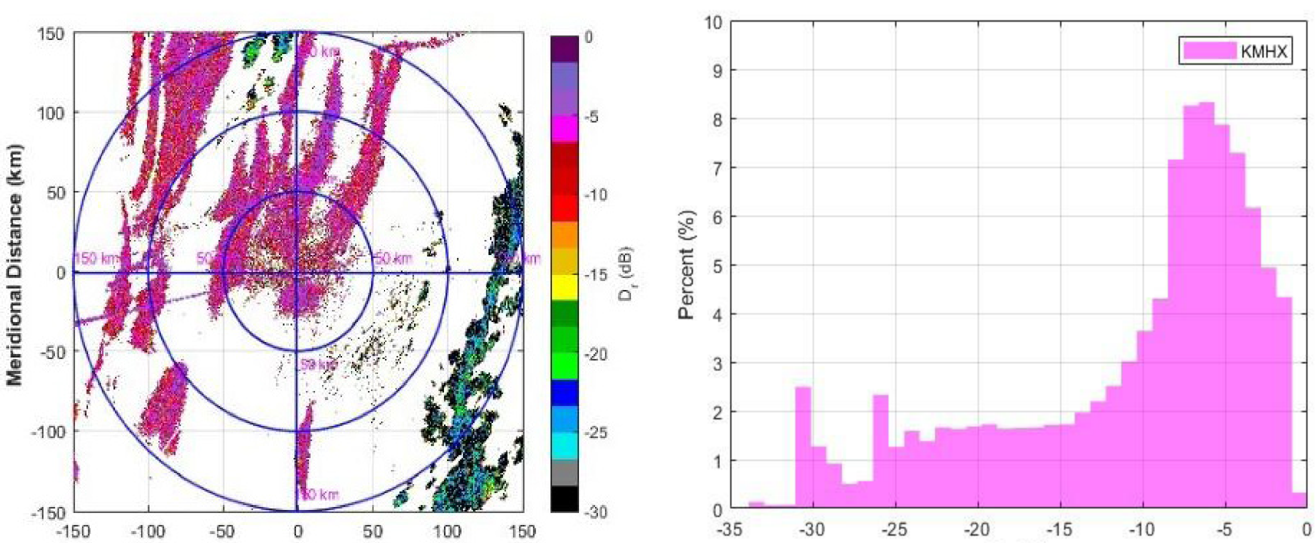


Figure 2-8: (left) Circular depolarization ratio field computed by using the data from the KMHX radar at antenna elevation equal to 0.5° (Scan made on October 19, 2011, at 22:23 UTC). (right) Histogram of circular depolarization ratio from (left).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Djordje Mirković, Valery Melnikov
Project Title: Electromagnetic scattering of complex shapes
Relevance to NOAA: Improving weather and water predictions, and developing next-generation observational capabilities

The research on electromagnetic scattering covers the scattering of hail and pyrogenic particles. Until this initiative, computational electromagnetics had not been used extensively in modeling hail due to its complexity. However, the recent publication of a library of mathematically created rough hail shapes has highlighted the need for obtaining more realistic naturally occurring hailstone shapes for more accurate scattering calculations. Understanding and accurately gauging hail size is crucial for NOAA's mission to protect lives and property. With the introduction of the Advanced Technology Demonstrator (ATD) radar and observations of LDR, there is a growing interest in hail signatures. CIWRO's Computational Electromagnetic Modeling (CEM) bridges the gap between the limited LDR calculations of hail and rough hailstone models. The focus of this project is on modeling ash particles using simplistic shapes derived from images of ash on vehicles. This novel approach aligns with NOAA's efforts to enhance wildfire detection through polarimetric radar observations. By modeling ash particles and calculating polarimetric signatures, we aim to improve early wildfire detection using polarimetric radars. Given that particles in the air cannot be simplified as spheres, a CEM approach is essential for accurate modeling. The outcomes of this research include six journal publications, one database publication, and three conference presentations.

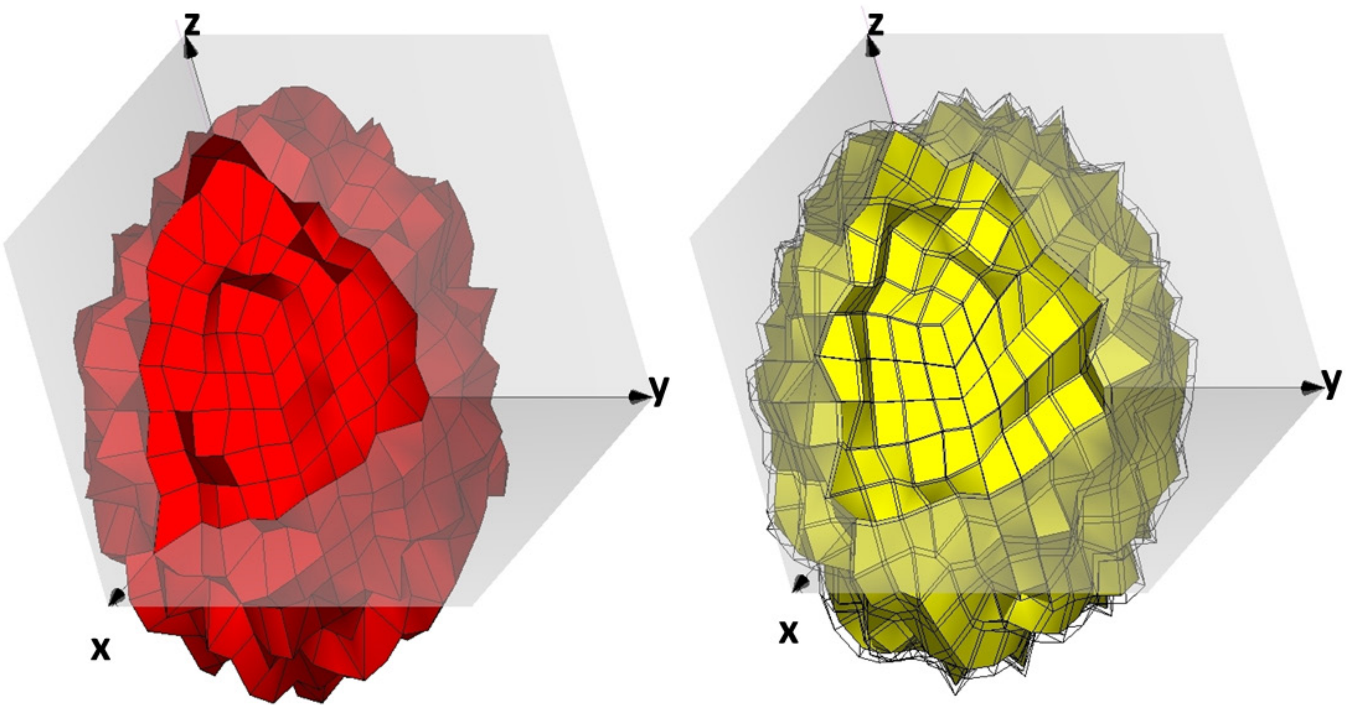


Figure 2-9: Three-dimensional models of rough hail, a single layer representing dry ice (red) and water coated (yellow), water layer can be observed as thin black mesh above the yellow ice core.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributor: Valery Melnikov
Project title: Linearization of radar receivers
Relevance to NOAA: This project supports the NOAA mission by improving observation quality or stewardship.

Radar receivers of WSR-88Ds are nonlinear, i.e., the output differential reflectivity (Z_{DR}) values depend on the powers of input signals. The radar receivers consist of two major parts: the radio-frequency (RF) part with the Low Noise Amplifiers (LNA) as the major nonlinear components and intermediate-frequency (IF) part with the digitizer as the major component. Both system parts, i.e., RF and IF circuits, contribute to nonlinearity. The left panel of the figure below presents the system Z_{DR} offset on NSSL's WSR-88D radar (KOUN). It can be seen that the system Z_{DR} increases with decreasing input signals. This means that Z_{DR} values in weak radar echoes were positively biased by the radar receiver. To make Z_{DR} measurements with an accuracy of 0.2 dB, the system Z_{DR} offset should be lower than 0.1 dB. To make the Z_{DR} response linear, an algorithm was designed (output is shown in the right panel). It can be seen that the Z_{DR} response after applying the algorithm is linear within ±0.1 dB. Outcomes from this project include 3 conference presentations and 2 technical reports to the Radar Operations Center (ROC).

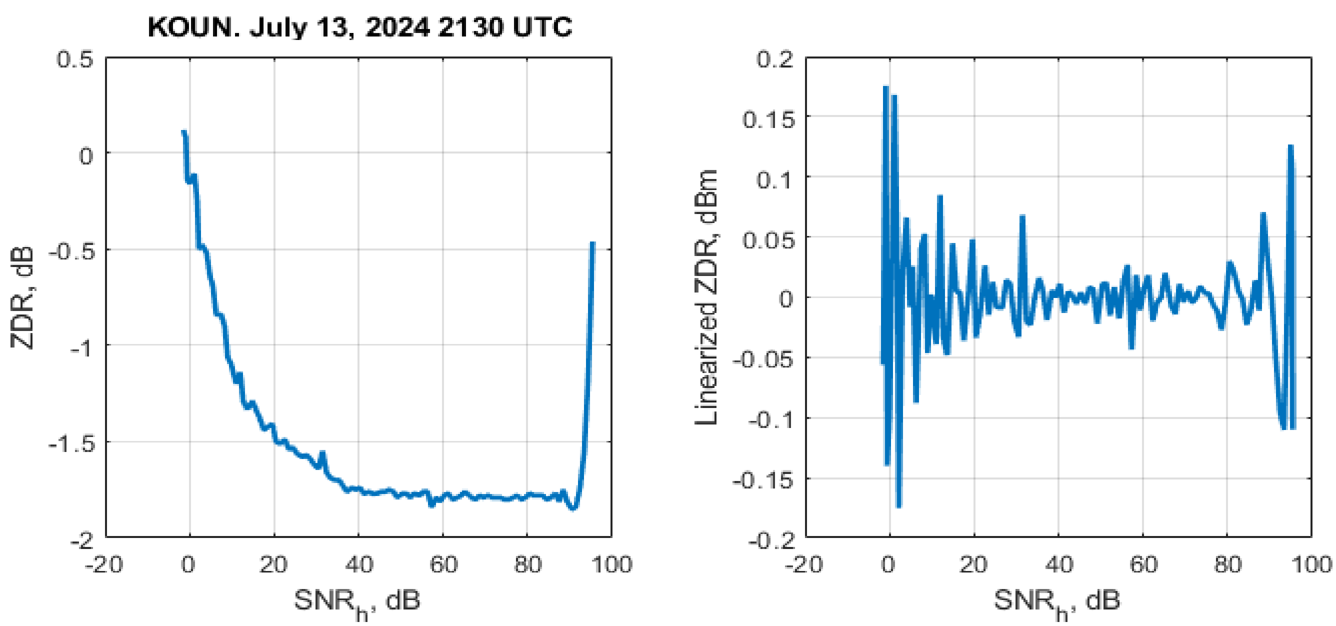


Figure 2-10: (left): measured Z_{DR} offset as a function of input signals. (right): linearized Z_{DR} response.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributor: Valery Melnikov
Project title: Temperature impacts on ZDR measurements
Relevance to NOAA: This project supports the NOAA mission by improving observation quality or stewardship.

Dual polarization WSR-88D radars operate in various regions. Ambient temperatures may range from -30°C in Alaska to more than +40°C in Arizona. This project investigates the dependence of differential reflectivity (Z_{DR}) on ambient temperature. An example of the findings is presented in the figure below. The left panel depicts time series of temperatures in KTLX radar subsystems which show wide temperature variations from about -20°C to +27°C in February 2021. The central panel shows time series Z_{DR} contributions from the antenna, transmitter, and receiver to the total system Z_{DR} offset. One can see that these contributions vary strongly. The right panel presents the system Z_{DR} offset and varying temperature. It can be seen that the Z_{DR} offset strongly correlates with temperature. The radars are equipped with an automatic Z_{DR} calibration system. Our analysis showed that the automatic system Z_{DR} calibration effectively compensates for the temperature variations. This is an important conclusion that indicates that no additional coolers/warmers are needed for the radar equipment.

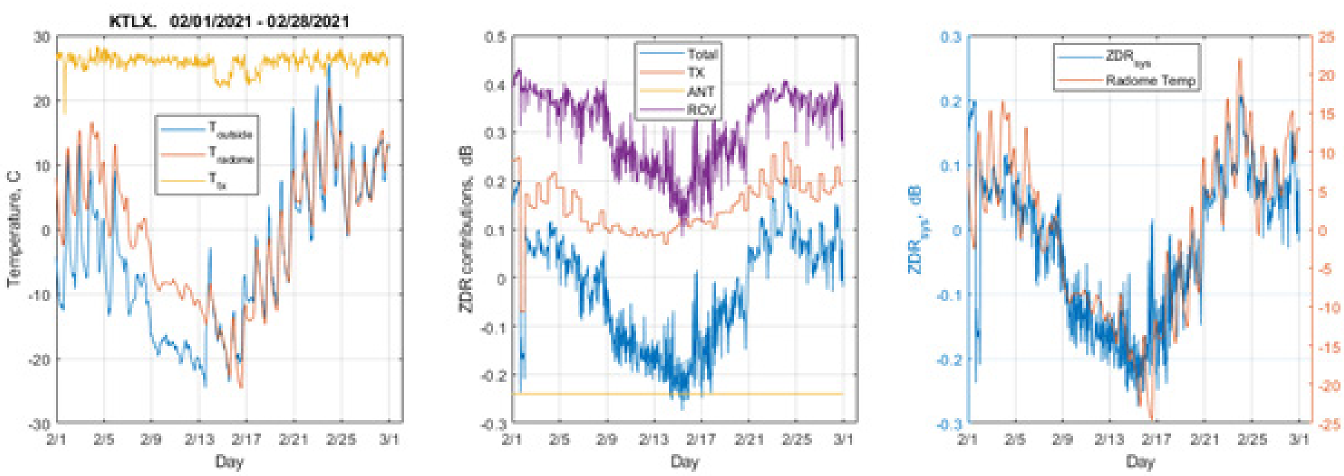


Figure 2-11: (left): Temperature variations in various KTLX radar subsystems for February 2021. (center): contributors to the system Z_{DR} offset. (right): The system Z_{DR} offset and corresponding temperature.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributor: Valery Melnikov
Project title: The impact of radar differential phase upon transmission on polarimetric variables
Relevance to NOAA: This project supports the NOAA mission by improving observation quality or stewardship.

NEXRAD radars transmit orthogonally polarized waves shifted in phase which is called differential phase upon transmission (DPT). The impacts of DPT on radar variables from hail were studied in the project. It was shown that DPT may significantly change the measured differential phase and correlation coefficient of signals from hail. It was also concluded that the differential phase exhibits an increase in hail cores. In the bottom panel of the figure, an enhanced area of the differential phase can be seen. Radial profiles of phase and correlation coefficient are shown in the right panel. The increase in phase (red curve) is obtained as a deviation of values from the mean (yellow line). It was found that this increase is caused by hail. The amplitude of the bump in differential phases correlates with the hail size. Tangible outcomes from this project include 3 formal journal papers, 3 conference presentations, and 1 scientific report for the Radar Operations Center (ROC).

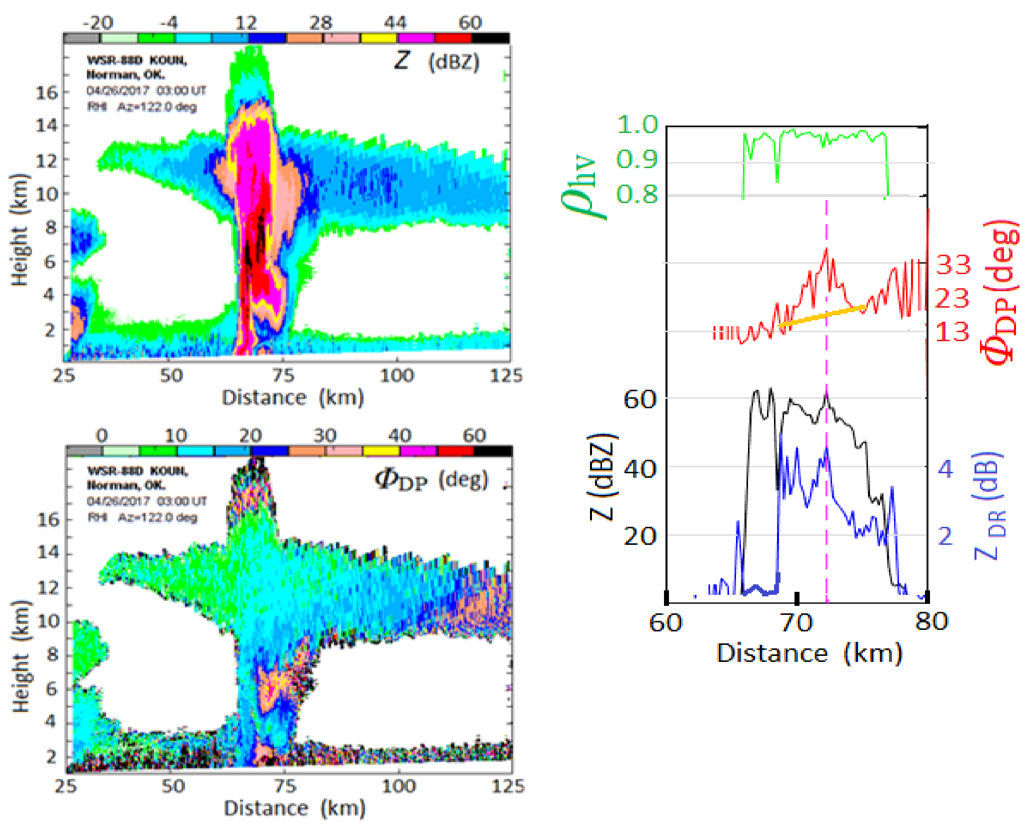


Figure 2-12: (left): Vertical cross-sections of reflectivity and differential phase from a hailstorm. (right): Radial profiles of radar variables through the reflectivity core.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Jiaxi Hu, John Krause, Alexander Ryzhkov
Project Title: Calibration of differential reflectivity using dry aggregated snow
Relevance to NOAA: This project supports the NOAA mission by improving observation quality and/or stewardship

In this study, we focus on the use of dry aggregated snow (DAS) routinely observed just above the melting layer (ML) and below the dendritic growth layer (DGL) bottom in stratiform precipitation assuming that the intrinsic value of differential reflectivity (Z_{DR}) in DAS varies between 0 and 0.2 dB depending on the intensity of snow and its degree of aggregation. We utilize quasi-vertical profiles (QVP) of polarimetric radar variables providing accurate measurements of Z_{DR} above the ML or above surface during cold season scenario. The most critical part of the calibration methodology is to identify DAS as opposed to other snow types with a much wider distribution of Z_{DR}. Several criteria for DAS identification have been developed. These include the value of maximum reflectivity (Z) and Z gradient above the ML up to DGL bottom, minimal value of the cross-correlation coefficient in the ML, and the depth of the cold part of the storm above the DGL. This calibration technique was tested for a large number of storms of different types and it was demonstrated that the achieved accuracy of the suggested Z_{DR} calibration is within 0.1 dB. Tangible outcomes from this project include 1 formal journal article, 2 conference presentations, and 1 algorithm ready for transition to NWS operations.

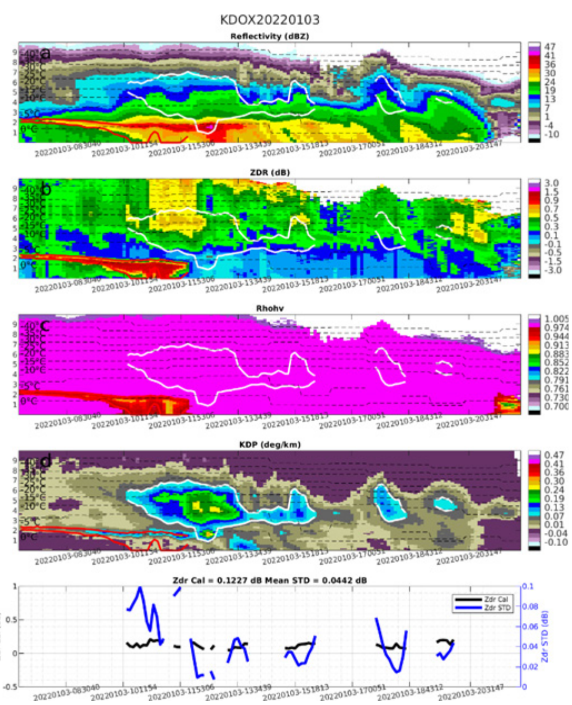


Figure 2-13: Warm/cold transitional season case example using the proposed algorithm. QVP time series between 0000 UTC to 2400 UTC 1 Jan 2022 near Dover AFB, DE (KDOX), WSR-88D radar. (a) reflectivity, (b) differential reflectivity, (c) specific differential phase, (d) correlation coefficient, and (e) algorithm output, including Z_{DR} bias (black contour, panel e) and Z_{DR} standard deviation (blue contour).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Valery Melnikov, Precious Jatau
Project title: Detecting birds and insects using machine learning and improving the VAD method.
Relevance to NOAA: This project supports the NOAA mission by improving observation quality or stewardship.

The Velocity-Azimuth-Display method (VAD) is used to obtain the wind from radar data. This method suffers from contaminations from flying birds. Birds are active flyers and bias the VAD output significantly. In this project, we designed an algorithm that eliminates bird echoes and measures the wind from clear air (Bragg scatter) and insects. The algorithm significantly reduces wind biases in the VAD method. The left panel in the figure shows echoes from birds (blue) and insects/Bragg (red) distinguished by the algorithm. The central panel depicts the wind bias of up to 10 m/s caused by the birds. The right panel presents wind bias after eliminating the bird echoes. Tangible outcomes from this project include 2 formal journal papers, 4 conference presentations, and 1 algorithm delivered to the NWS/ROC.

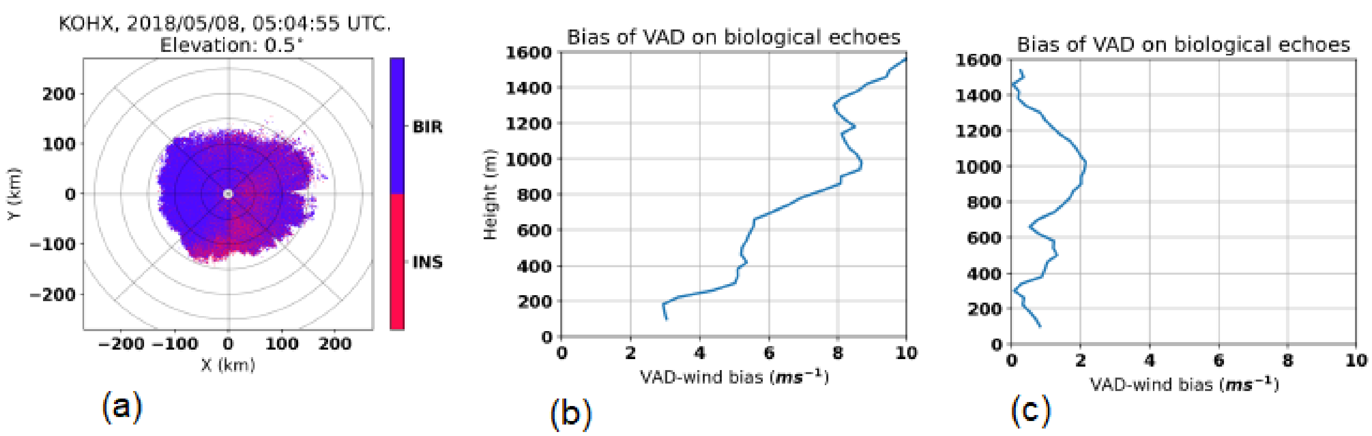


Figure 2-14: (a): The proposed algorithm distinguishes radar echoes from birds (blue color) and insects of Bragg scatter (red color). (b): bias in the VAD wind caused by birds. (c): bias of the wind after eliminating contaminations from birds.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributor: Jami Boettcher
Project Title: WSR-88D elevations sidelobe contamination study
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions.

As part of the SENSR Data Quality study, Boettcher analyzed simulations of varying levels of elevation sidelobe contamination (ESLC), noting the varying ways this type of contamination manifests in the data. The most problematic form is a false circulation, i.e. an “imposter”. Evan Bentley at the SPC provided a set of case examples from 2016-2018 to Boettcher, as well as a quantitative analysis of the percentage of false alarm tornado warnings issued where imposter circulations were present across the CONUS. This collaboration led to a study of these cases by Boettcher, who developed a novel cross-section visualization technique as a qualitative confidence builder that ESLC was contributing to an apparent circulation. The results of our study included the tornado warning false alarm “cost” of misinterpretation of these imposter signatures, an understanding of their origin, i.e. the main lob is surrounded by sidelobes that extend much farther than a few degrees in azimuth, and the relationship between the returned power from the main lobe vs. the ***cumulative*** returned power from the sidelobes. Diagnostic techniques were developed specifically for NWS forecasters that fit within existing workflow patterns of warning decision making. The work resulted in 1 journal publication.

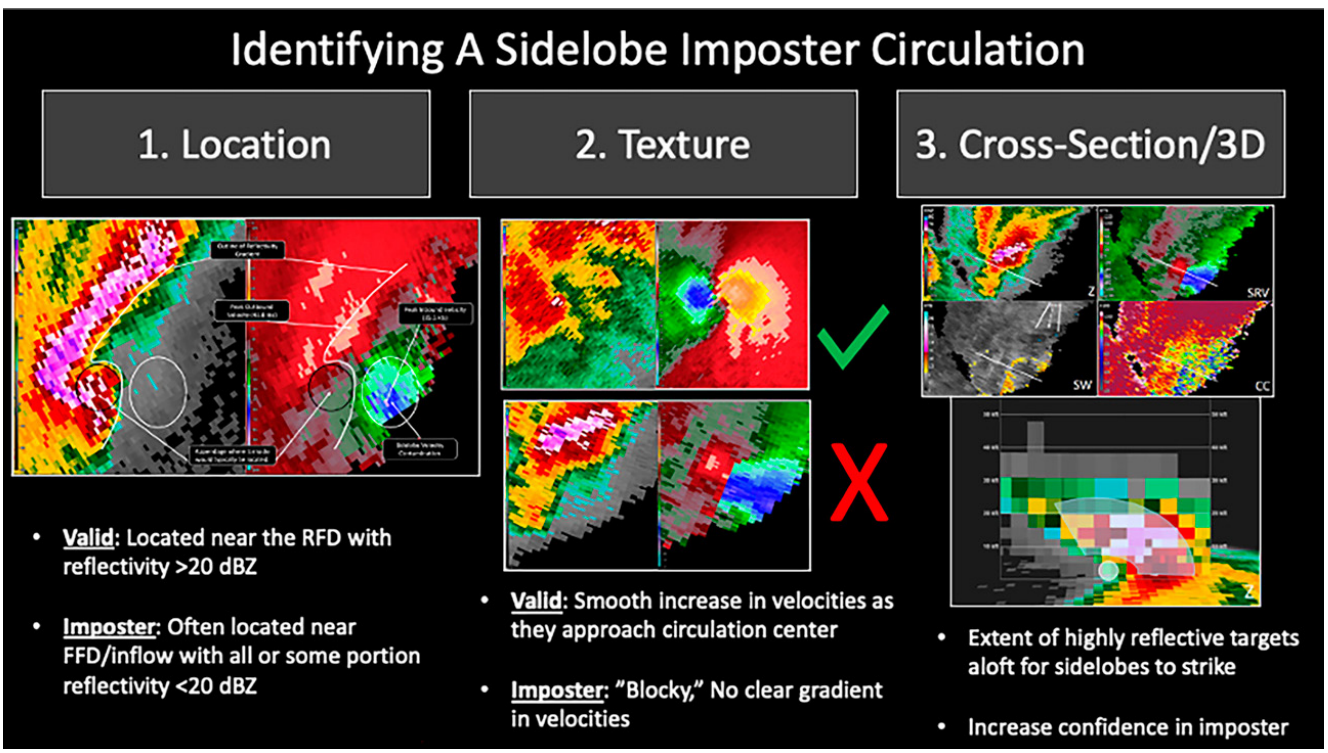


Figure 2-15: Summary of diagnostic techniques for NWS forecasters to identify imposter circulations in real time.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Pengfei Zhang, Alexander Ryzhkov
Project Title: Computation of rain rates in areas of wind farms
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds and improving observation quality.

To meet requirements for clean energy, more and more wind farms are deployed globally. This presents challenges for weather radar users. In order to mitigate the contaminations of wind turbines on radar measurements and accurately estimate rain rate in areas of wind farms, a new dual-pol radar QPE method with wind farm correction is developed. First, the method detects the wind-turbine-contaminated radar echoes. Second, it replaces the contaminated reflectivity measurements with median values of surrounding uncontaminated reflectivity. Third, rain rate is estimated using specific attenuation, R(A). The performance of this new method was evaluated by comparing between radar QPE without/with wind farm correction and the measurements of rain gauges that are located in the areas of wind farms. The results show that the accuracy of rainfall estimations is improved in the areas of wind farms after applying the proposed algorithm. Tangible outcomes from this project include 2 conference presentations and the transition of the algorithm to the NWS.

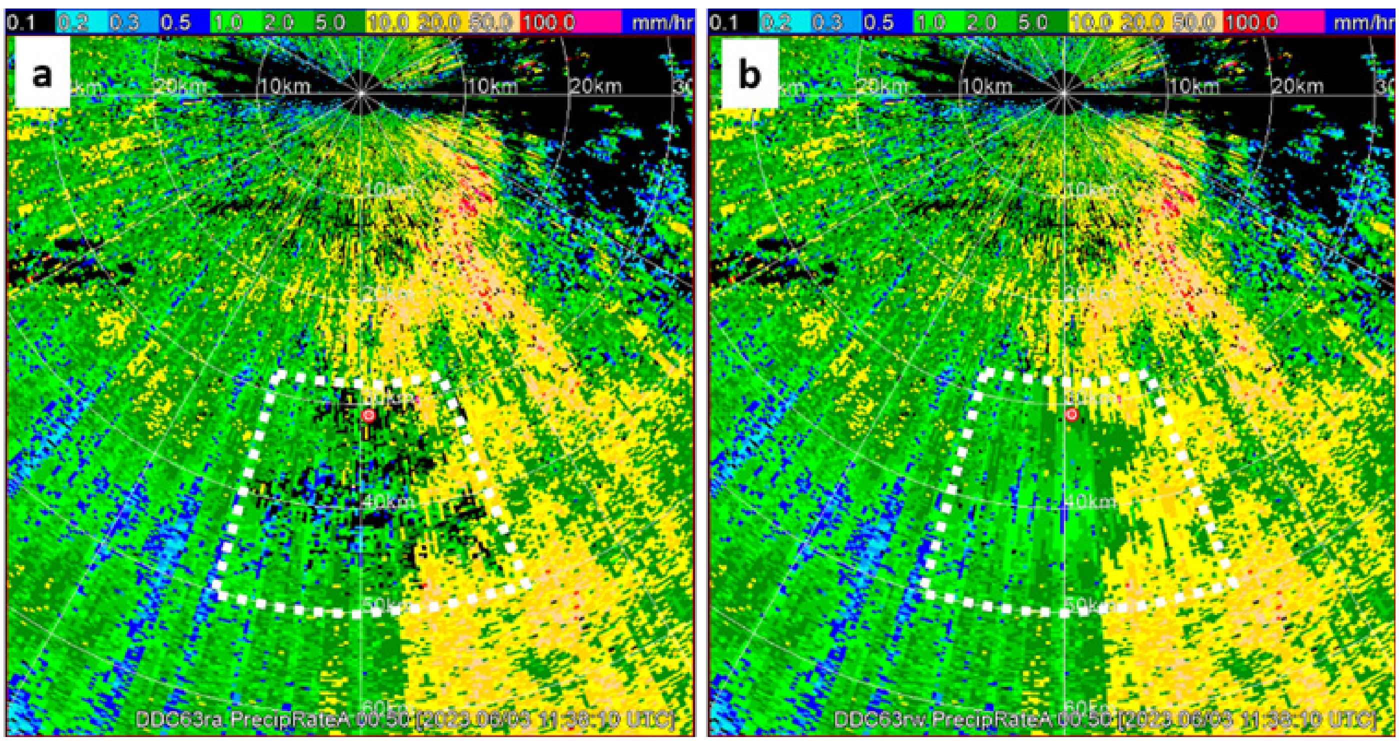


Figure 2-16: Rain rate estimated without (a) and with (b) wind farm correction at the elevation angle of 0.5°. The black holes within the white dash polygon indicate the detected wind turbine contaminated radar range gates. The red dot indicates the location of the rain gauge.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: John Krause, Jiaxi Hu
Project Title: New cell identification and tracking algorithm
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

The current method for detecting and tracking storms in radar data developed by Johnson et. al. (1998) is over 20 years old. Since that time, many new and improved methods have been proposed, most of which detect and track the area of the strom rather than the storm's centroid. This project has implemented the Multi-Cell Identification and Tracking (MCIT) method (Hu et al. 2019) and will soon compare it to other methods and recommend a method for implementation on the WSR-88D network. Improving storm cell identification is a required first step in identifying storm-based quantities such as storm strength, hail size, and tornadic probability. This project has had one R2O software transfer and 1 journal article.

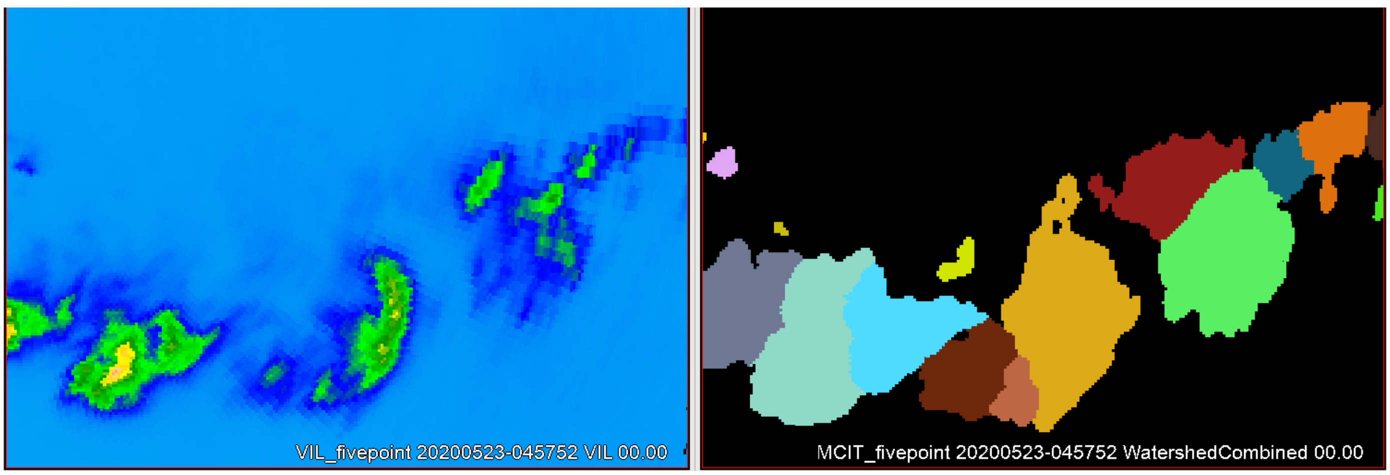


Figure 2-17: VIL (Vertically Integrated Liquid water) data collected by KFDR on 20200523 (left) used to create MCIT area-based storm cells (right).

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Alexander Ryzhkov, John Krause
Project Title: New melting layer detection algorithm
Relevance to NOAA: This project supports the NOAA mission by Developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

The current melting layer algorithm only considers radar data collected between 4 and 10 degrees of elevation and is unable to properly identify the height of the melting layer in winter scenarios where significant weather like ice pellets and freezing rain are likely. The new melting layer detection algorithm (Ryzhkov and Krause 2022) works with lower elevation data to make a more complete picture of the melting layer near the ground. Furthermore, the new melting layer detection algorithm operates at each location in the domain and can identify when the melting layer is at the ground or not present at all. Improvements from the algorithm can be expected in the hydroclassification and QPE outputs. This work has led to 2 conference presentations, 1 journal article, and has been transitioned to operations.

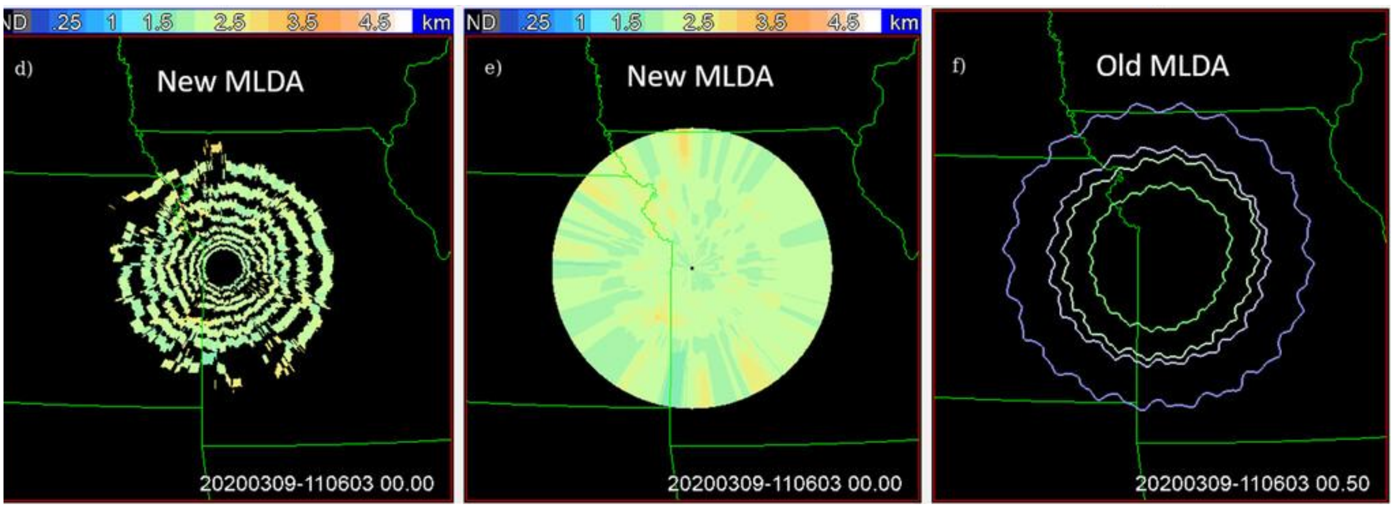


Figure 2-18: The map of the ML bottom height Hb reconstructed from eight antenna elevations (left) before and (center) after interpolation.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Marcus Johnson, Thea Sandmæl, Brandon Smith
Project Title: Single-radar azimuthal shear
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions.

Azimuthal shear is a radial velocity-derived shear single-radar product used to analyze severe storms, particularly rotational features. Azimuthal shear measures the rotational shear, which is calculated as the across-azimuth derivative (relative to the radar) of radial velocity. Azimuthal shear can help identify areas of rotation within storms, such as mesocyclones or vortices in a squall line. This product can be particularly useful for detecting weak or non-obvious circulations that might not be easily discerned in base radial velocity. Azimuthal shear is being transitioned to operations through collaboration with the NWS Radar Operations Center. CIWRO has provided code and support to facilitate the transition of azimuthal shear into Radar Operation Center's testing systems to start the evaluation process that comes prior to being fully available in operations. Azimuthal shear was recently included in a HWT experiment to gauge operational utility in severe weather warning operations. Feedback from this experiment showed that azimuthal shear was deemed as a very useful tool to provide situational awareness and confidence building for use in simulated warning operations as shown in the figure below. Tangible outcomes from this project include one conference presentation and one product ready for transition to NWS operations. External partners involved in this project include NWS/ROC.

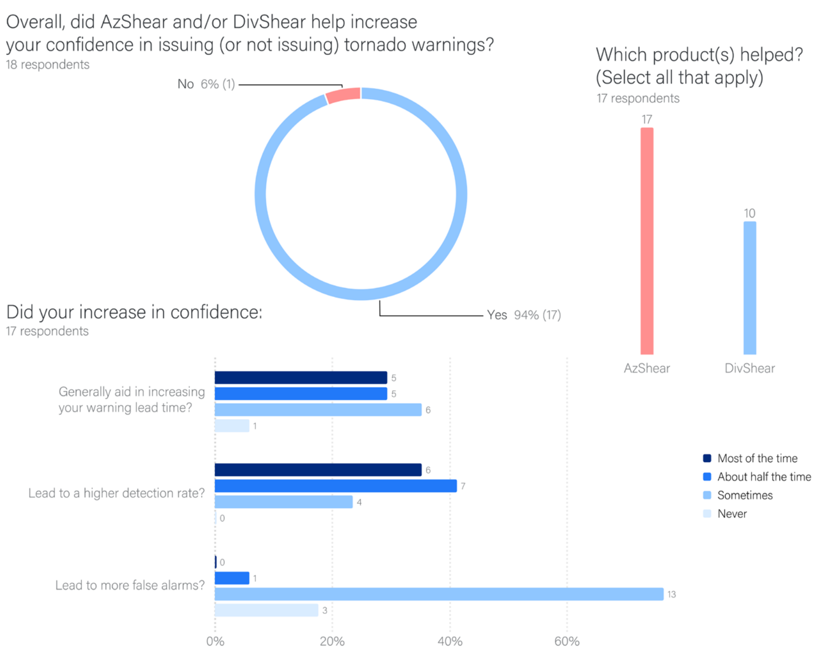


Figure 2-19: Survey results from the 2024 HWT Experimental Warning Program Radar Convective Applications experiment. Eighteen NWS forecasters answered questions about azimuthal shear after using the product in simulated severe warning operations.

CIWRO Themes: Weather Radar and Observations, Mesoscale and Stormscale Modeling, Forecast Application Improvements
CIWRO Contributors: Rachel Miller, Andrew Wade, Matthew Flournoy, Anthony Lyza, Geoff Marion, Branden Katona, Lauren Pounds
Project Title: Examining the characteristics, environments, and processes associated with severe storm hazards
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

This project seeks to investigate the evolution of severe storms and their hazards, the environments that lead to these hazards, and the processes that distinguish these environments from storms without hazards, with specific focus on the Southeast U.S. This work uses a combination of field observations collected by the science team [e.g., Propagation, Evolution, and Rotation in Linear Storm (PERILS)], long-term observational data (e.g., storm reports, radar data), and modeling simulations to understand where, when, and why severe storm hazards occur with a focus on tornadoes. Recent key conclusions include confirming that tornadic storms producing more than one tornado tend to have stronger lower-tropospheric vertical wind shear. Additional work has also shown that U.S. Southeast tornadic environments are characterized by stronger vertical wind shear and more CAPE than in non-tornadic environments as shown in the figure below. Salient findings have been conveyed to the SPC (SPC) and have been used to augment their internal sounding analysis of Southeast U.S. tornado environments. Tangible outcomes from this work so far are eight conference presentations, 11 journal articles, one field experiment led, one graduate student supervised, and one funded proposal. External partners involved with this project include NWS/SPC, OAR/NSSL, and OU/SoM.

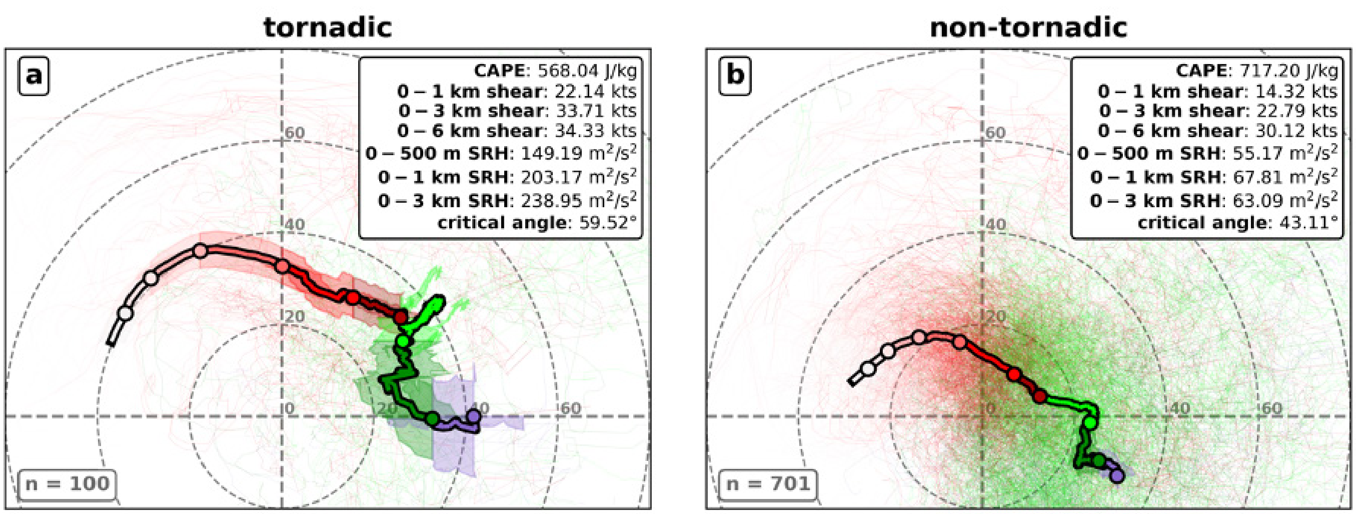


Figure 2-20: A plot comparing the average wind speed and direction with height from soundings in a) tornadic environments vs b) non-tornadic environments. Averaged common environmental parameters used by forecasters are shown in the figure inset.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Brandon Smith, Thea Sandmæl
Project Title: The new mesocyclone detection algorithm
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions.

The new mesocyclone detection algorithm is a completed single-radar algorithm designed for the WSR-88D radar network that utilizes radial velocity-derived azimuthal shear to detect and track rotation within thunderstorms. This algorithm has been evaluated by NWS and U.S. Air Force forecasters in two HWT experiments in 2019 and 2021). Through this, it has been found to be a useful tool to operational forecasters as a way to increase their situational awareness and to build their confidence during warning operations, representing an innovation upon its predecessor algorithm. This new algorithm is utilized within the Advanced Weather Interactive Processing System II that is used operationally by the NWS. Tangible outcomes from this project include three conference presentations and one algorithm ready for transition to NWS operations. External partners involved in this project include NWS and NWS/ROC.

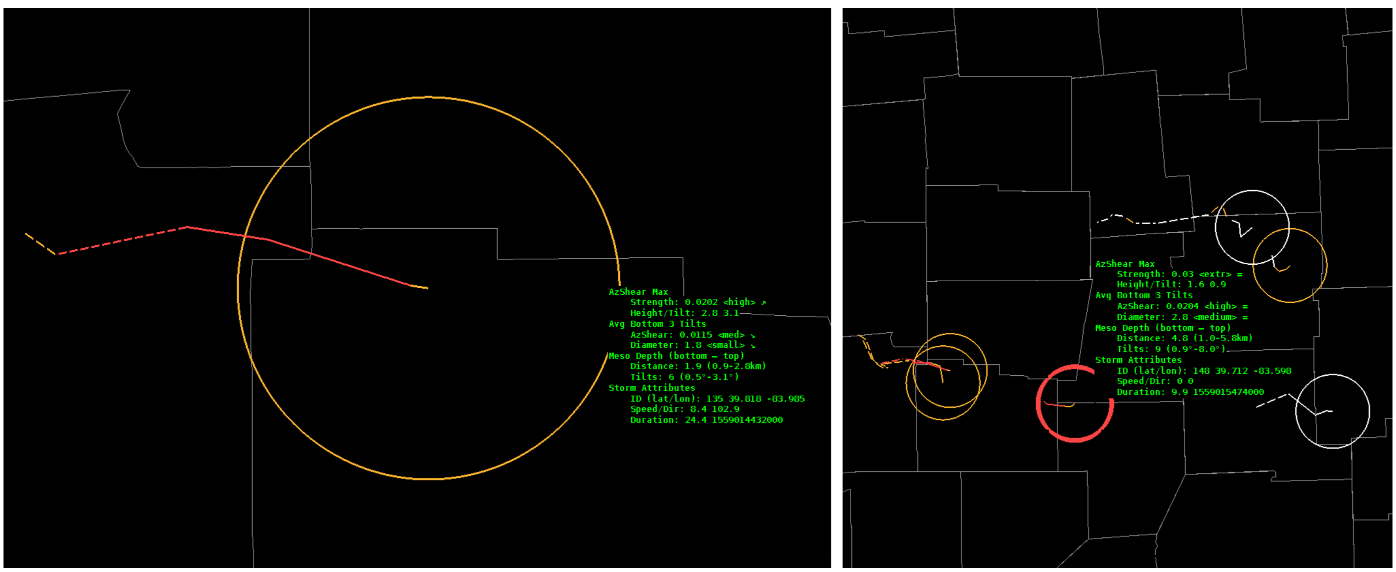


Figure 2-21: Examples of NMDA detections as displayed within AWIPS-II. The circle represents the location of the detection, the solid and dashed line represents the detection's past location history, and the green text highlights the detection's attributes such as strength and size.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Alexander Ryzhkov, Pengfei Zhang, Jiaxi Hu
Project Title: Improving R(A) / R(KDP) QPE algorithms
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

The most advanced radar rainfall estimation algorithm implemented on the MRMS platform named Q3DP primarily relies on the joint use of the R(A) and R(KDP) relations. It became operational in October 2020 and demonstrated very good performance, particularly for heavy rain associated with flash floods. The quality of the Q3DP QPE is illustrated in the plot showing the results for hurricane Helene. Despite the overall good performance of the existing Q3DP algorithm, there is still a room for further improvement, which is a primary objective of this project. Several important modifications have been recommended recently for the R(A) and R(KDP) methodologies. The new methodology explicitly takes into account the spatial variability of the raindrop size distribution and temperature dependence of the specific attenuation A. In a modified version of the algorithm, a power-law R(KDP) relation used for estimation of heavier rain in Q3DP has a variable multiplier which should be automatically optimized as a function of time and location using a combination of KDP and Z. This would help to reduce heavy rain underestimation in tropical cyclones which is visible in the plot for hurricane Helene. Preliminary evaluation of the modified QPE methodology shows promising results. The recommended modifications of the Q3DP algorithm are described in the journal article “Suggested modifications of the S-band polarimetric radar rainfall estimation algorithm” by A. Ryzhkov, P. Zhang, and J. Hu.

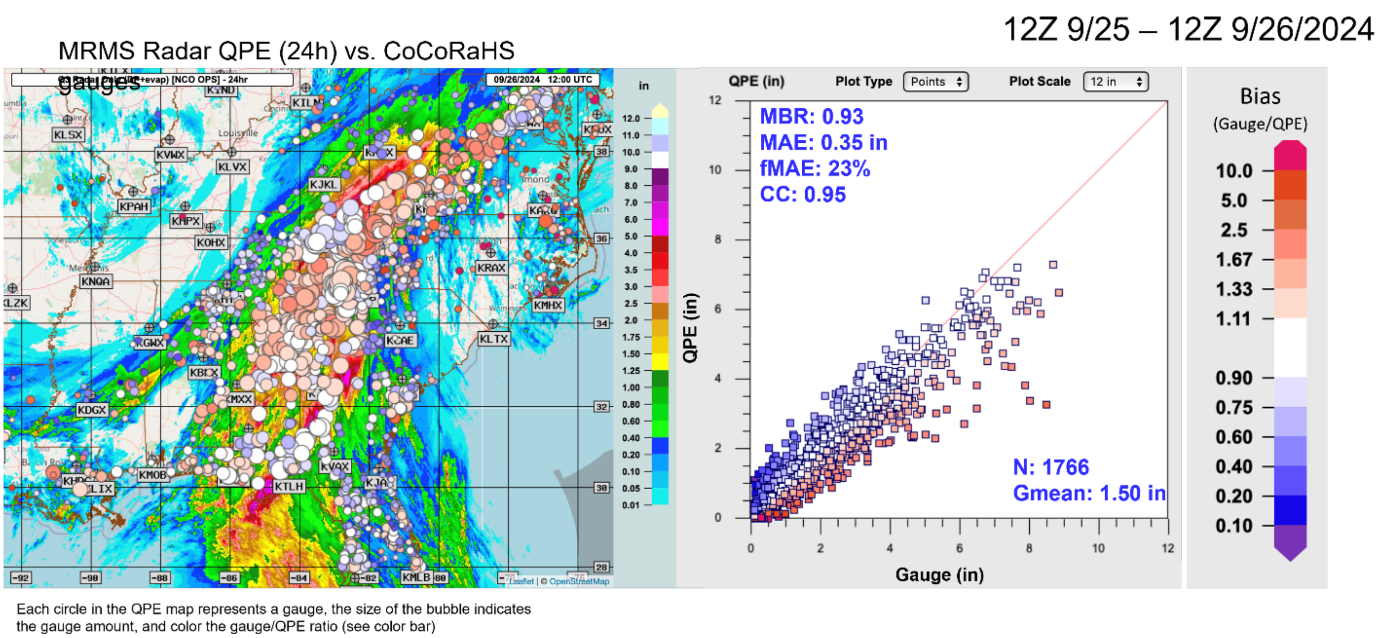


Figure 2-22: Hurricane Helene. Left panel - rain accumulation map and bubble plot showing radar / gauge ratio (white color indicates unbiased estimate). Right panel – scatterplot of 24-h rain totals measured by gauges vs their radar estimates using the Q3DP QPE algorithm.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributor: Petar Bukovcic
Project Title: Polarimetric radar ice pellets and/or freezing rain hydrometeor discrimination
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds and improving observation quality and/or stewardship.

A novel algorithm for discrimination between the ice pellets and freezing rain/rain was developed using only polarimetric radar data: vertical gradients of the radar variables reflectivity (Z), specific differential phase (K_{dp}), differential reflectivity (Z_{DR}), and correlation coefficient (ρ_{hv}). The algorithm searches for classical refreezing polarimetric signatures (decrease in Z and ρ_{hv}, and initially increase than decrease in Z_{DR} and K_{dp} with decreasing heights), and works well in the presence of the ice phase in the radar volume. In addition, the algorithm discriminates three stages of refreezing: 1) dominant freezing rain species with some ice nuclei/pellets in the radar volume, 2) dominant ice pellets with some freezing rain in the radar volume, and 3) mostly ice pellets in the radar volume. The initial testing in more than dozen events showed very encouraging results. External partners involved in this project include Federal Aviation Administration (FAA).

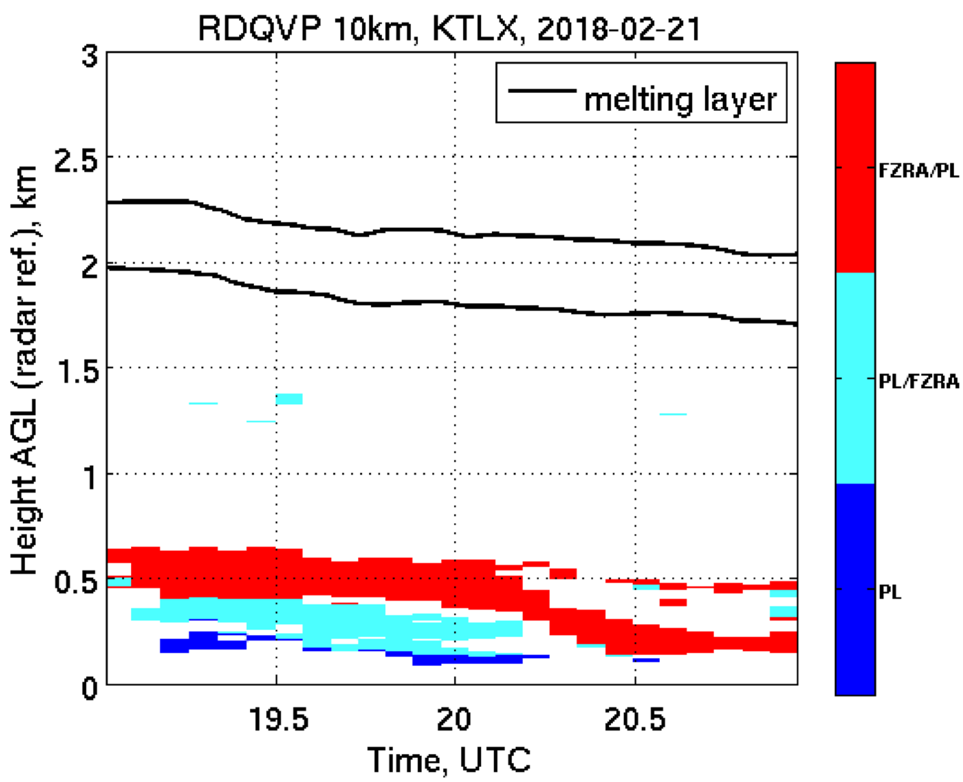


Figure 2-23: KTLX (10 km radius) range-defined quasi vertical profile output for ice pellets (PL) – freezing rain (FZRA) detection algorithm. Red color represent stage (1) in refreezing, with dominant FZRA and some PL in radar volume, cyan represents stage (2) with dominant PL with some FZRA in the radar volume, whereas dark blue color is stage (3) of refreezing with mostly PL in the radar volume; thick black lines represent melting layer. 21 February 2018.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Petar Bukovcic, Alexander Ryzhkov
Project Title: Polarimetric snow estimates aloft with an in-situ measurements of rain and freezing rain originating from stratiform events
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds and improving observation quality and/or stewardship.

This project examined several stratiform precipitation events with bright-bands below 3.5 km altitude. For “high” altitude (>2km) bright-band events, polarimetric snowfall rate, denoted by $S(K_{dp}, Z)$ (Bukovčić et al. 2020), and estimated from range-defined quasi-vertical profiles or column vertical profiles, denoted by $S(IWC, D_m)$, slightly to moderately underestimate the amounts of rain on the ground. This is for roughly 500 to 1000 m above the melting layer with values of the canting angle distribution (σ) for aggregated snow between 20 and 30 deg. Both polarimetrc estimates are in good agreement with measurements of rain on the ground if the values of σ are between 30 and 40 deg. For relatively low bright-band altitudes (<1 km), both polarimetric estimates from 500-1000 m above the melting layer perform very well, similarly to pure snow cases. These results indicate that the precipitation mass flux is conserved in the transition between the solid and liquid phase precipitation if there is no advection or sublimation/evaporation occurring, and may serve for the expansion of polarimetric snow QPE validation database. Polarimetric snow QPE is related to polarimetric ice water content estimation (IWC, Oue et al. 2025). Outcomes of this work include 1 journal article.

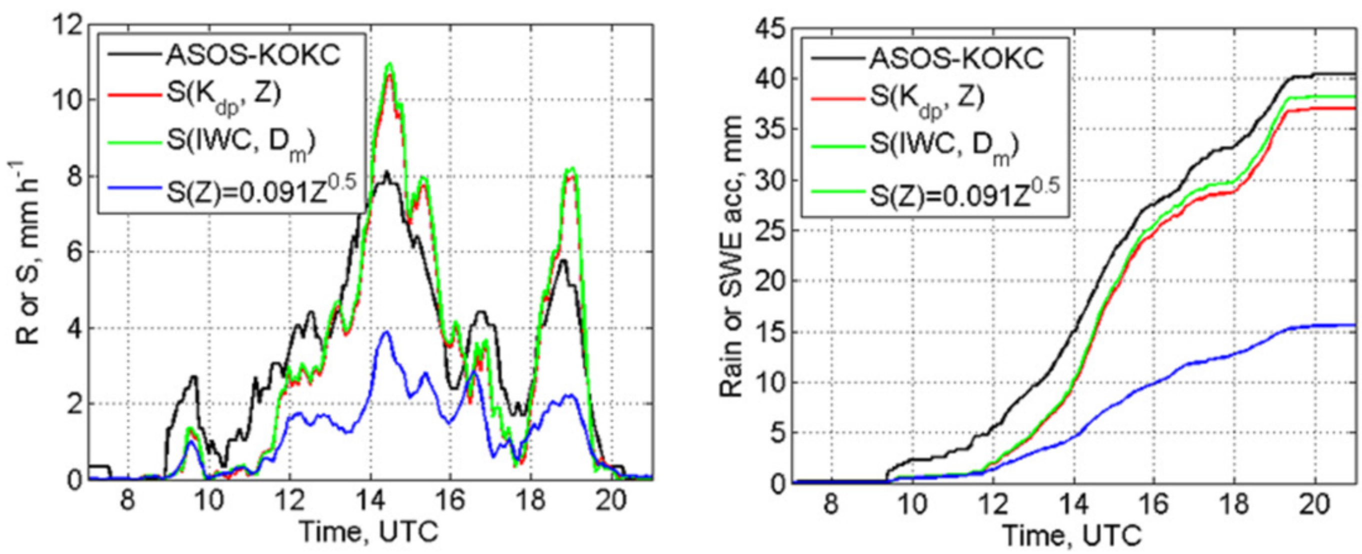


Figure 2-24: Left panel: Instantaneous rainfall rates from ASOS KOKC measurements (black curve), and KTLX 10 km column vertical profile (CVP) output of: Bukovcic et al. (2020) $S(K_{dp}, Z)$ relation (red curve), standard S(Z) (blue curve), and polarimetric $S(IWC, D_m)$ relation (green curve); Right panel shows respective accumulations; 2020-10-26.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Edwin Dunnavan, Jacob Carlin, Alexander Ryzhkov, Greg McFarquhar
Project Title: High-resolution snowstorm measurements and retrievals using cross-platform multi-frequency and polarimetric radars
Relevance to NOAA: This project supports the NOAA mission by optimizing platform-agnostic data and information and by creating/improving a trusted analysis of record for model verification/nowcasting.

This project directly compared polarimetric radar retrievals of snow from Range-Height Indicator (RHI) scans of a mobile X-band radar with coincident nadir-pointing airborne multi-frequency retrievals. This project is the first to perform such a high-resolution set of retrievals between polarimetric and multifrequency snow retrievals. Results indicate that the snow mean volume diameter retrieved from polarimetric radars can deviate by almost 1.0 mm compared to similar retrievals from airborne radars. Additionally, this project investigates the types of snowflakes using the well-known "triple frequency" diagrams. The shape of these triple frequency diagrams suggested the possibility that snowflakes were generally aggregates of needles. This project was conducted with external collaborators from NASA and has resulted in 1 conference presentation and 1 journal article (Dunnavan et al. 2023).

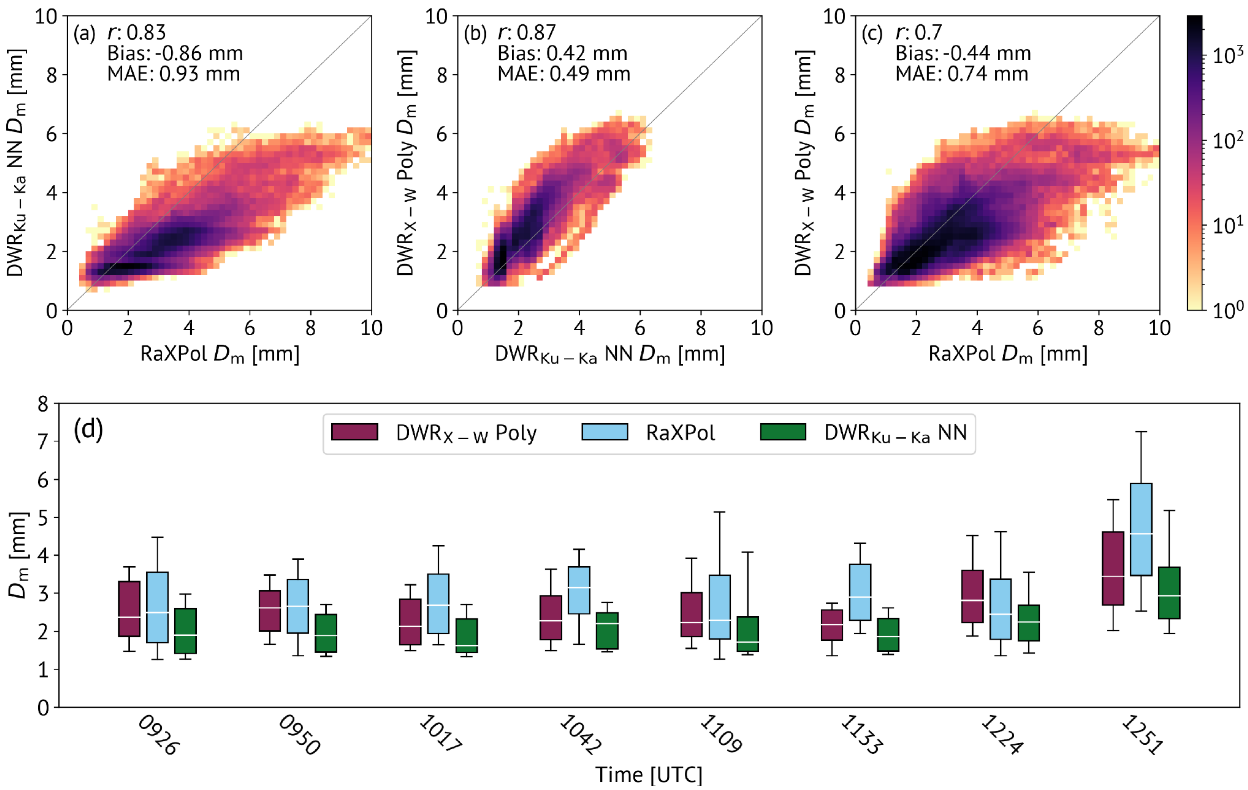


Figure 2-25: (Top row) Joint distributions comparing snow mean volume diameter (D_m) radar retrievals using three different measurements from two different platforms (one from the ground-based X-band mobile RAXPOL radar and two different retrieval methods from multifrequency radars aboard the ER-2 aircraft). (Bottom row) Box plots of D_m for each retrieval for 8 overpass time periods throughout the case.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Petar Bukovcic, Jacob Carlin, Andrew Rosenow, Alexander Ryzhkov
Project Title: Development and testing of an algorithm for polarimetric radar extinction coefficient/visibility estimation in snow
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds and improving observation quality and/or stewardship

In this project, we derived theoretical and empirical relations for polarimetric extinction/visibility estimates utilizing polarimetric radar variables specific differential phase K_{dp} and reflectivity Z, with the explicit treatment of orientation and shape factors, F_o and F_s, related to the width of the particle canting angle distribution and aspect ratio. The previous relation (Bukovcic et al. 2021) with the explicit treatment of the gamma particle size distribution shape parameter (μ) and degree of riming parameter (f_{rim}) was recently upgraded. We tested the novel relation on several moderate to heavy snow events with positive results – there is a slight to moderate improvement in comparison to previous polarimetric and conventional algorithms. We also purchased a forward scatter sensor (extinction/visibility sensor), which was successfully installed and is being used for data collection at the Kessler's farm since January 2024. Tangible outcomes from this project include 1 formal journal article and 1 conference presentation.

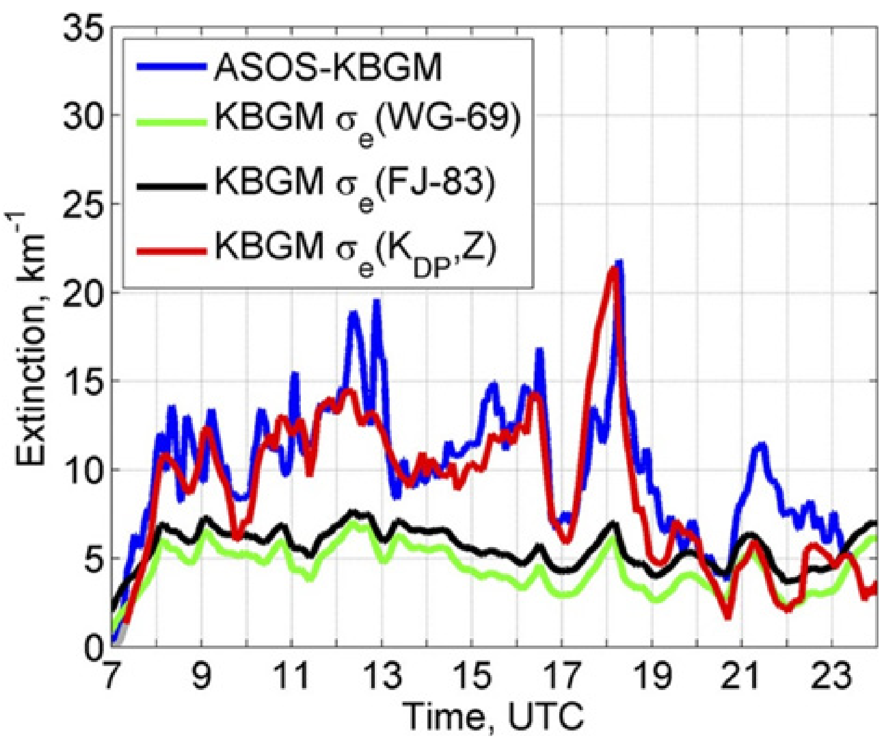


Figure 2-26: The evolution of the extinction coefficient σ_e measured with the KBGM ASOS gauge (blue curve), and estimated from KBGM radar range-defined quasi vertical profile: σ_e(Warner and Gunn 1969 – WG69) (green curve), σ_e(Fujijoshi et al. 1983 – FJ83) (black curve), and $\sigma_e(K_{dp}, Z)$ (red curve) at 350 m AGL; 2017-03-14.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Petar Bukovcic, Alexander Ryzhkov
Project Title: Development and testing of the polarimetric radar snow QPE algorithm
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds and improving observation quality and/or stewardship

This project focuses on the development and improvements of the polarimetric snowfall rate (S) quantitative precipitation estimation (QPE). The most recent polarimetric snow relations utilizing specific differential phase (K_{dp}) and horizontal reflectivity (Z), S(K_{dp}, Z), optimized with the explicit treatment of microphysics parameters degree of riming (f_{rim}), and shape of the gamma particle size distribution (μ) (in addition to particle shape and orientation parameters, F_s and F_o), are validated with WSR-88D data. The initial tests showed significant improvements in comparison to standard and optimized, S(Z) and $S_o(D_m, Z)$, and slight to moderate improvements compared to previously published polarimetric snow QPE relation (Bukovcic et al. 2020) in moderate to heavy snow events. In addition, the relation in Bukovcic et al. (2020) is utilized for the hybrid polarimetric-conventional snow QPE prototype algorithm, which is in final testing stages for WSR-88D operational implementation. Tangible outcomes from this project include 3 formal journal articles and 8 conference presentations, 1 algorithm in final testing stages before transition to radar operation center (ROC) for WSR-88D implementation.

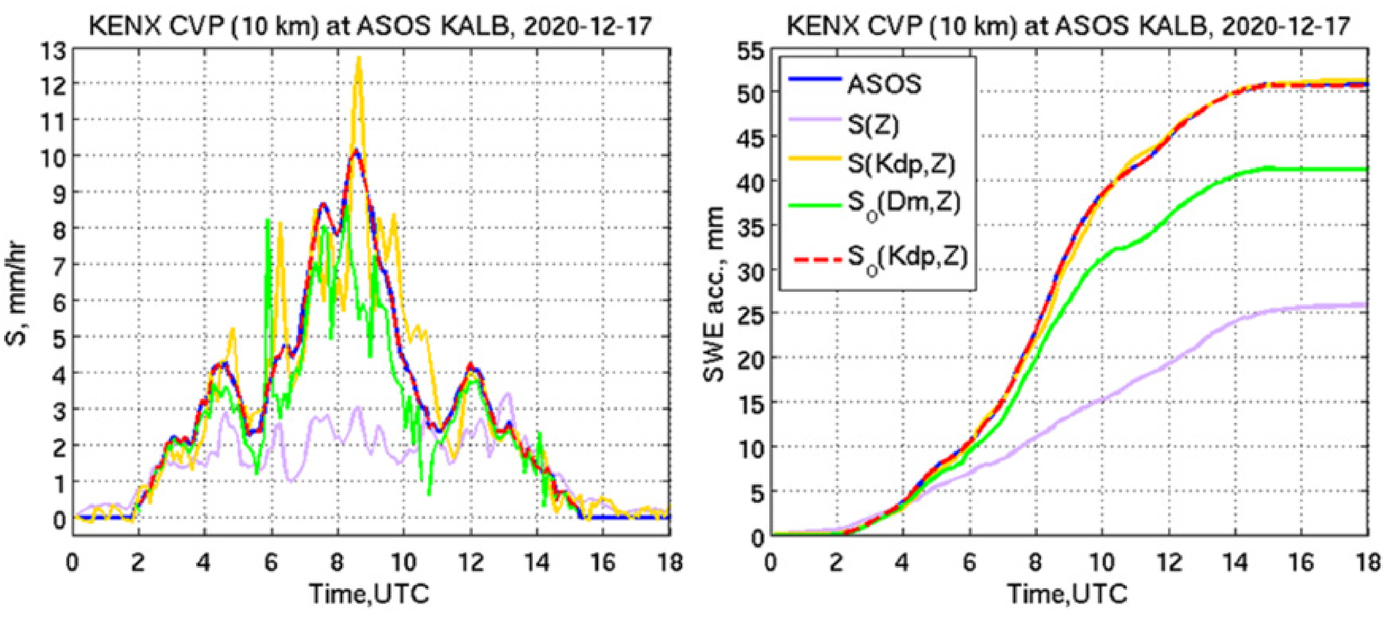


Figure 2-27: Instantaneous snowfall rates from ASOS KALB measurements (blue curve), and KENX 10 km column vertical profile (CVP) output of Bukovcic et al. (2020) relation (yellow curve), standard S(Z) (lilac curve), and optimized (subscript o) relations – S(Z) with mean volume diameter, $S_o(D_m, Z)$ (green curve), and 2024 polarimetric S_o(Kdp, Z) (broken red curve); Right panel shows respective accumulations; 2020-12-17.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Dean Meyer, Petar Bukovcic
Project Title: Evaluation of new Dual Polarization snow QPE
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and enhancing capabilities for the Radar Next program and/or WSR-88Ds.

This project evaluates a new snow quantitative precipitation estimates (QPE) algorithm that utilizes dual pol information to estimate snow liquid water content. The current operational Snow Accumulation Algorithm uses reflectivity (Z) to snow rate [S(Z)] relations, as determined for pre-defined geographical regions, to estimate snow liquid water equivalent (SWE) values. However, this usually results in a large amount of variability and error as SWE is dependent upon other atmospheric variables besides Z. Hence, over the past five years, a new Dual Pol Snow QPE algorithm has been developed that utilizes Dual Pol information to estimate SWE. Currently, the algorithm is being tested and refined using a diverse set of snowfall events. The new algorithms performance and the legacy SAA algorithm are being assessed via comparison with quality-controlled gauge data. Test QPE products have 0.5 deg azimuthal and 0.25 km radial resolution. In the future, the Dual Pol Snow QPE algorithm will be intended for use by forecasters as well as input for a variety of hydrological models. Tangible outcomes from this project include 2 Radar Operation Center (ROC) reports, 4 ROC Technical Interchange Meetings.

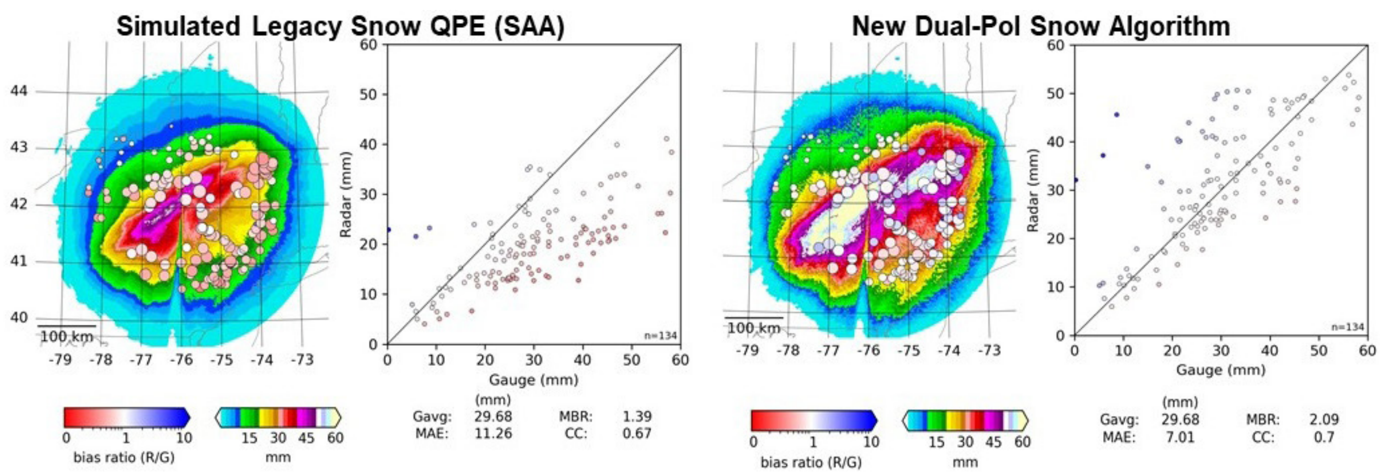


Figure 2-28: 24-h QPE SWE accumulations, gauge bias bubbles and QPE vs Gauge scatter plots as derived from the current operational Snow Accumulation (simulated SAA, top) and that derived from the New Dual Pol Snow (bottom) QPE algorithms for the period ending 1200 UTC 17 December 2024. The SAA uses reflectivity data alone to estimate snow liquid water equivalent while the Dual Pol QPE utilizes Dual Pol information.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Edwin Dunnavan, Jacob Carlin, Marcus Johnson, John Krause
Project Title: Identifying winter precipitation type using a modified spectral bin classifier
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

This project developed an operational NEXRAD algorithm (sfcHCA) for classifying surface precipitation using WSR-88D radar data. The sfcHCA algorithm serves as an improvement to the Hydrometeor Classification Algorithm (HCA; Park et al. 2009) that is available from each WSR-88D radar site as NEXRAD level 3 data. The sfcHCA uses a steady-state 1D discrete particle model to diagnose surface precipitation types within WSR-88D volumes and merges this output with HCA data to provide surface precipitation types at each radar gate. The sfcHCA utilizes several new WSR-88D products including Range-defined Quasi-Vertical Profiles (RD-QVPs) and the Melting Layer Detection Algorithm (MLDA) which are used to initialize the 1D particle model and to adjust the thermodynamic environments for each WSR-88D radar volume. The sfcHCA was validated using 225 cases taken from all available WSR-88D CONUS NEXRAD radar sites against more than 15,000 individual manned ASOS station reports and over 30,000 individual mPING reports. Probability of detection rates within 20 km of these observations were 95.7%, 79.3%, 76.7%, 70.2%, and 52.9% for rain, snow, wet snow, freezing rain, and ice pellets, respectively. The sfcHCA is currently being implemented in the Open systems Radar Product Generator (ORPG; Jain et al. 1997) and the algorithm has resulted in 1 conference presentation and 1 R2O transfer.

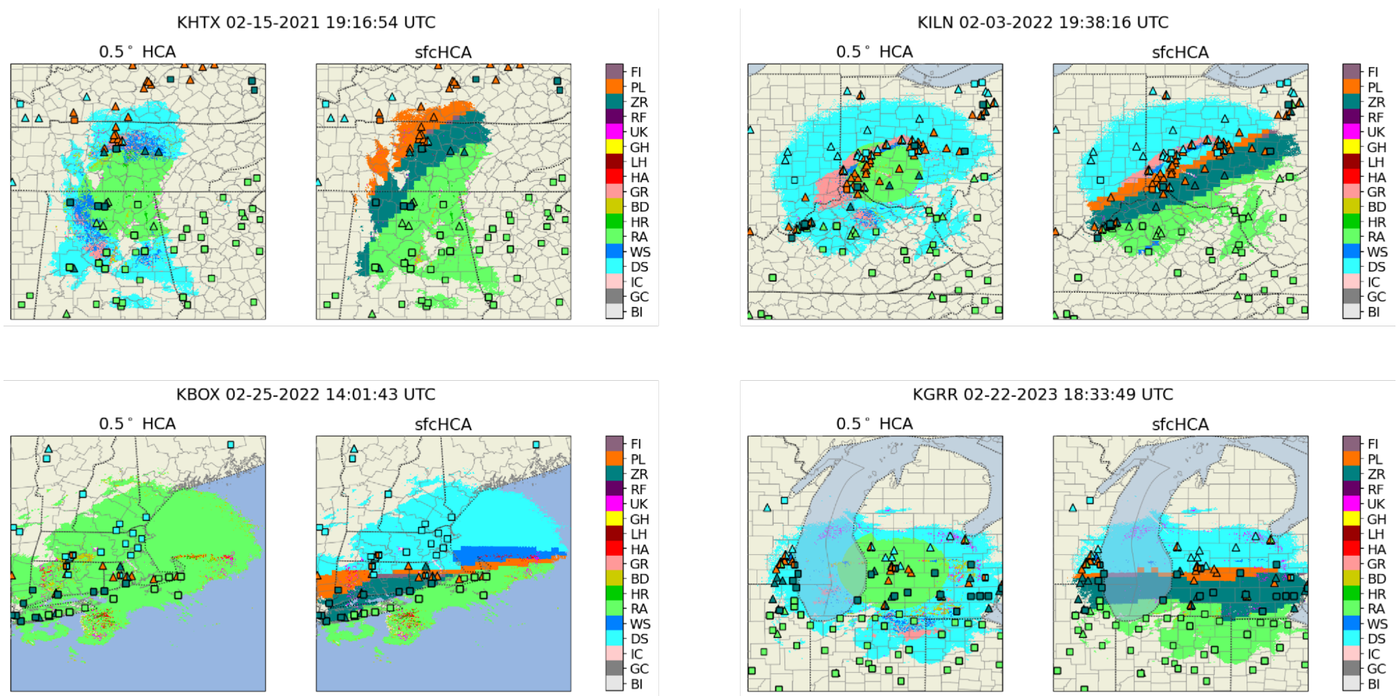


Figure 2-29: Example output of the new surface HCA (sfcHCA) algorithm compared to the current NEXRAD level III lowest-tilt HCA product from 4 different WSR-88D radar sites compared to ASOS (square) and mPING (circle) observations within +/- 10 minutes of radar volumes.

CIWRO Themes: Weather Radar and Observations
CIWRO Contributors: Edwin Dunnavan, Jacob Carlin, Alexander Ryzhkov, Petar Bukovcic, Jiaxi Hu, Greg McFarquhar
Project Title: Radar retrieval evaluation and investigation of dendritic growth layer polarimetric signatures in a winter storm
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds and optimizing platform-agnostic data and information.

This project evaluated Multi-radar/Multi-Sensor (MRMS) radar-retrieved ice particle size distribution parameters and aspect ratios against in situ aircraft measurements. This project found that the often-observed specific differential phase and differential reflectivity enhancement regions in the dendritic growth layer can be caused by either a large number of small, dry ice particles or by ice particles mixed with supercooled liquid droplets. Common radar retrieval equations were found to be biased compared to these in situ aircraft observations such that mean volume diameter retrievals were systematically underestimated by approximately 50% whereas ice particle number concentrations were systematically overestimated by over 100%. This project also found inconsistencies in radar retrievals of ice particle aspect ratios compared to in situ observations. This project was conducted with external collaborators from NASA and has resulted in 1 conference presentation and 1 journal article (Dunnavan et al. 2022).

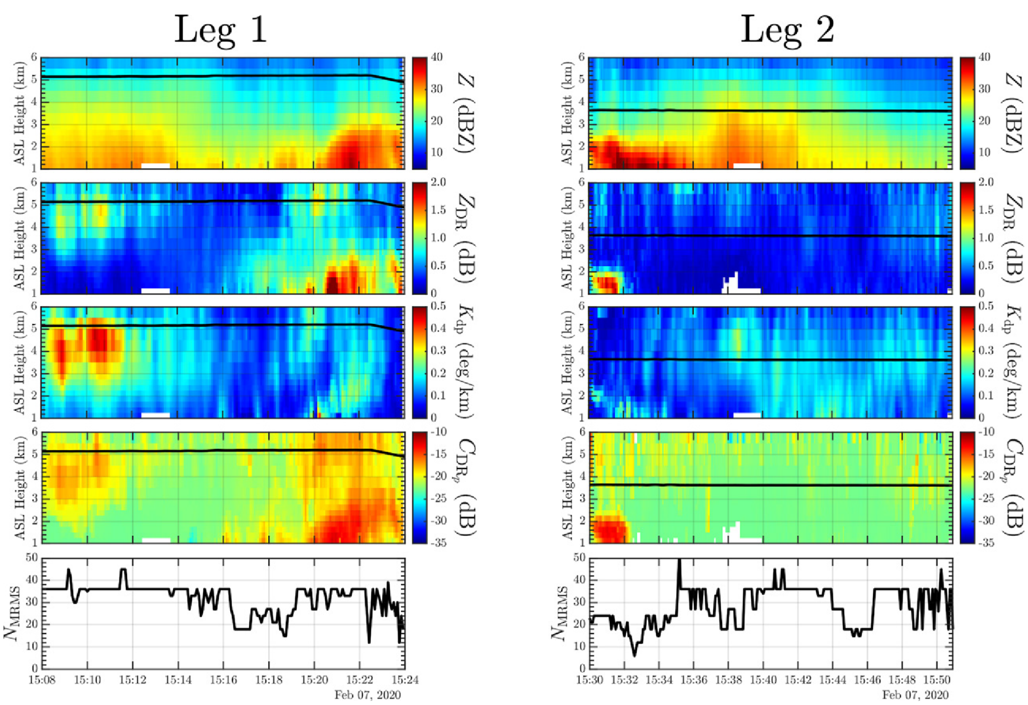


Figure 2-30: Comparison of MRMS polarimetric timeseries measurements of (from top to bottom): reflectivity, differential reflectivity, specific differential phase, and a circular depolarization ratio proxy with the NASA P-3 aircraft altitude (black lines) for two separate flight legs. The bottom row shows the number of unique MRMS points used to impute the values shown above to the P-3 aircraft horizontal location at each time (see Dunnavan et al. 2022 for more details).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributor: Petar Bukovcic
Project Title: Joint ASOS stations/polarimetric radar microphysics parameters retrievals in snowstorms
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds and improving observation quality and/or stewardship.

We derived and established a novel and innovative theoretical approach that involves snowfall rate and extinction from Automated Surface/Weather Observing Systems (ASOS) measurements and radar reflectivity, specific differential phase, and reflectivity difference from WSR-88D radar measurements. Radar measurements were used for retrievals of various microphysical parameters in the proximity of ASOS stations for complete and incomplete gamma distributions. The approach is upgraded to retrievals of particle orientations and shapes, as well as the shape (μ) and slope (Λ) Particle Size Distribution (PSD) parameters. The retrievals are directly related to the improvements and validations of polarimetric snow relations and numerical weather model parameterizations and validations. Tangible outcomes include 7 conference presentations.

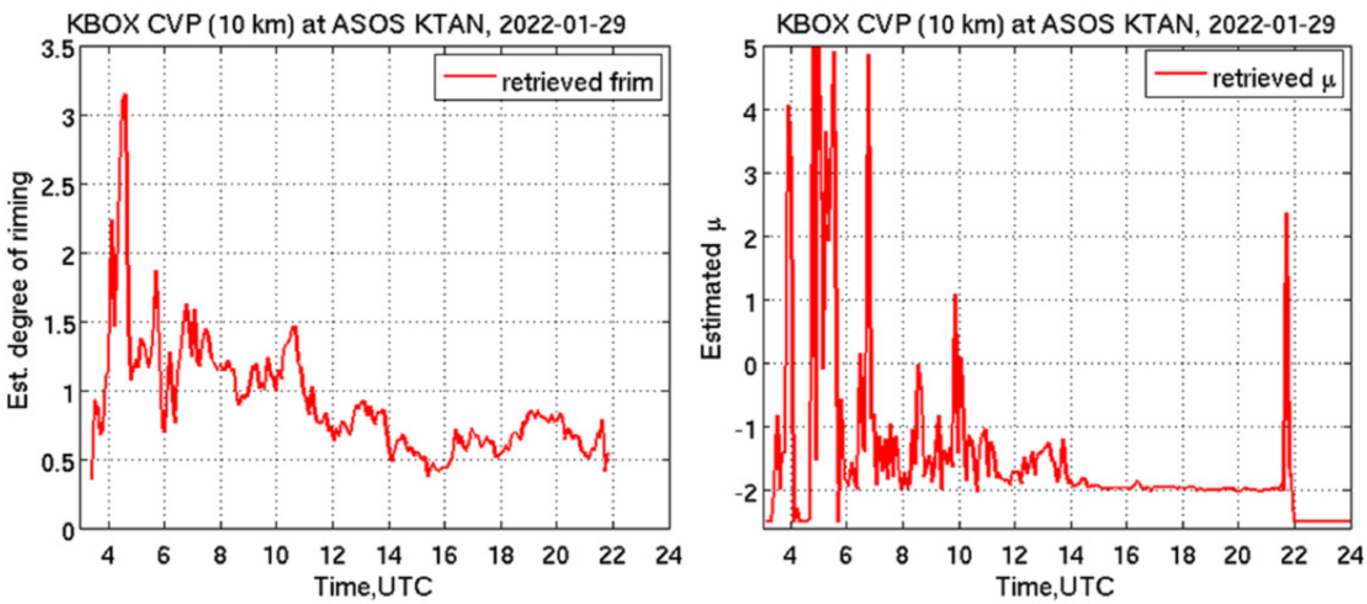


Figure 2-31: KBOX radar column vertical profile (CVP; 10 km radius) output of ASOS (KTAN)–radar microphysics parameters retrieval algorithm; left panel – degree of riming (f_{rim}); right panel – shape parameter (μ) of gamma particle size distribution; 29 January 2022.

CIWRO Themes: Weather Radar and Observations, Mesoscale and Stormscale Modeling, Forecast Application Improvements
CIWRO Contributor: John Krause
Project Title: Identifying ZDR columns in radar data with the hotspot technique
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

Differential reflectivity (Z_{DR}) columns in the scientific literature are often associated with lofted liquid water droplets supported by a strong updraft. The automatic identification of Z_{DR} columns in radar data has proven difficult due to the location of the updraft on the rearward side of the thunderstorm, which is adjacent to other Z_{DR} anomalies. Furthermore, automatic identification routines must contend with uncalibrated Z_{DR} data and radar anomalies like differential attenuation. The hotspot technique was developed to overcome these roadblocks. Using a hyper local approach and matching Z_{DR} column detections to storm cells, storm updrafts for each cell can be identified and tracked, allowing for additional information on the lifecycle of the storm, and providing information on storm growth, decay, hail size, and other hazards. This work has led to 1 conference presentation and 2 journal articles.

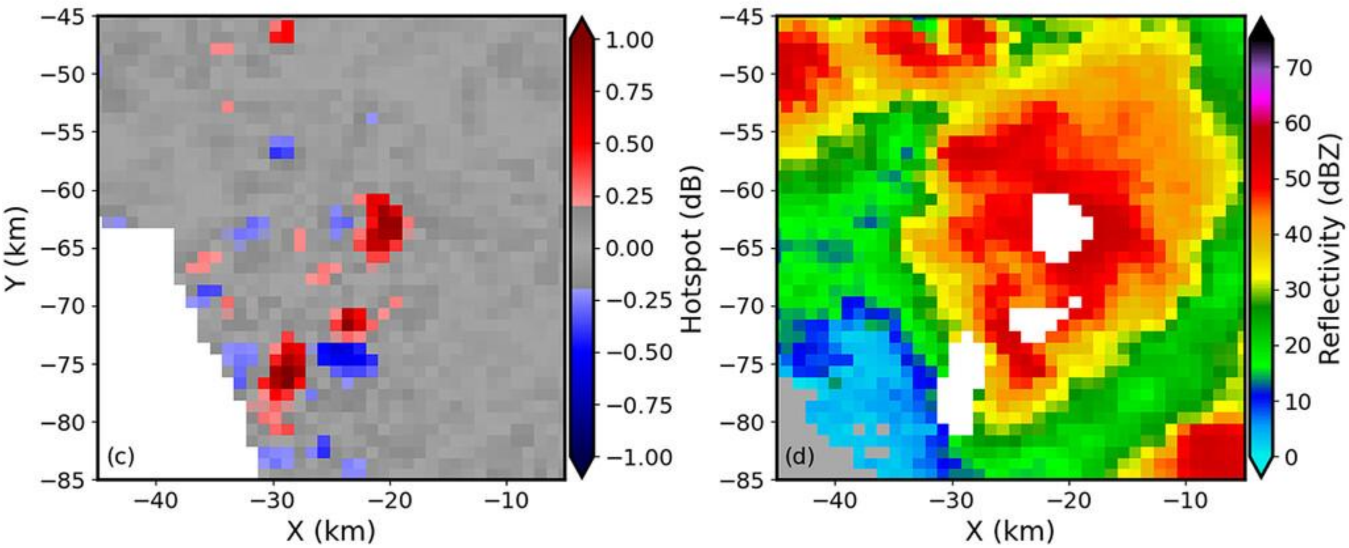
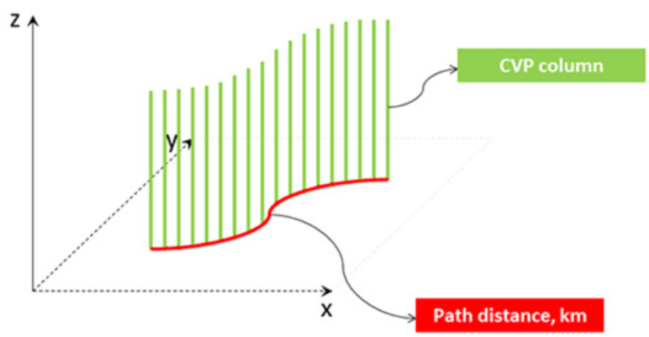


Figure 2-32: Examples of Z_{DR} hotspot and Z_{DR} hotspot objects (white) overlaid on reflectivity. All data from 0457 UTC 23 May 2020 at KFDR at the height of the −10°C isotherm (5.547 km AGL).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Petar Bukovcic, John Krause
Project Title: Path-CVP – Polarimetric radar data snapshot along the predefined path based on columnar vertical profiles
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds and improving observation quality and/or stewardship.

Recently introduced Columnar Vertical Profiles (CVPs) arrange polarimetric radar data collected via plan position indicator (PPI) scans in height vs. time format. A novel method for polarimetric radar data processing and visualization based on CVP, path-CVP (pCVP), representing the data in height vs. distance format, is introduced. pCVP is a snapshot of the polarimetric radar data along the arbitrary or predefined path (left panel image) with high spatial resolution. Monitoring and quantifying instantaneous weather conditions with polarimetric radar along the motorways, mountain overpasses, and aircraft paths during the descent and ascend from the runway are just some of the benefits the novel technique offers. For example, melting layer is clearly visible in all four radar variables (increase in Z, K_{dp}, and Z_{DR}, and decrease in ρ_{hv}) between 1.5 and 2.5 km, whereas refreezing layer (increase in K_{dp} and Z_{DR}, and decrease in Z and ρ_{hv}) is apparent in the lowest ~0.4-0.6 km along the flight path (right panel). The increasing distance from the radar and the size of the area used for CVP spatial averaging may limit algorithm's practical usage. Tangible outcome: 1 conference presentation.



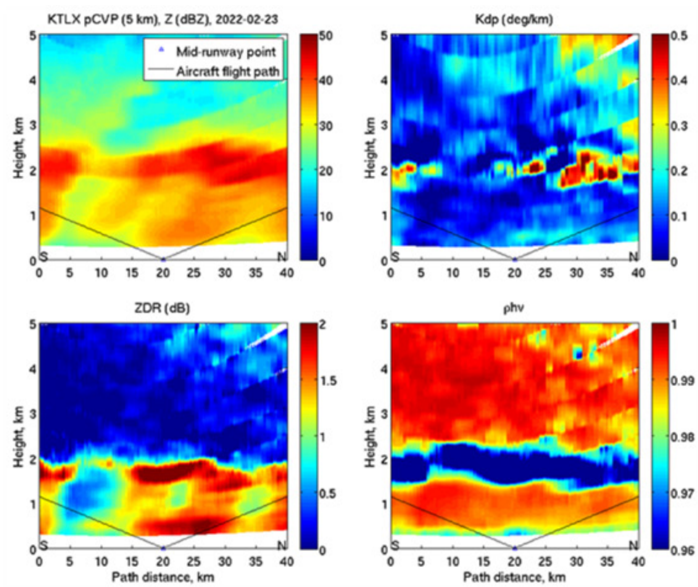


Figure 2-33: Left panel: pCVP construction from CVPs; right panel: KTLX pCVP of Z, K_{dp}, Z_{DR}, and ρ_{hv} aligned with OKC Will Rogers airport runway (located at 19-21 km path distance) in South-North (S-N) direction. Melting layer apparent at 1.5-2.5 km, and refreezing at ~0.4-0.6 km AGL; black lines represent simulated aircraft descend/ascend path; 1335 UTC, 2022-02-23.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Jiaxi Hu, Pengfei Zhang, Alexander Ryzhkov
Project Title: Process-oriented vertical profile technique
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds and developing reliable probabilistic guidance products.

The real-world morphologies of severe storms, particularly high-precipitation storm cells or tornadic supercells, are seldom confined to the shapes like a vertical column defined by the Column Vertical Profile (CVP) method. Many storm cells are tilted by shear instead of being vertically oriented. Moreover, the shape and size of the downdraft and updraft are not vertically uniform across different radar elevation scans. To address these challenges, this study proposed a novel Process-Oriented Vertical Profile (POVP) technique, which generates vertical profiles of dual-polarization radar variables within a vertically tilted column, taking into account only a selected percentile of radar variable within a broader contour at each radar scan. This technique was designed to capture user-defined processes within storms with spatial continuity. For demonstration purposes, this study employed contours defined by the 50th percentile reflectivity. The novel POVP technique successfully captured the microphysics characteristics within the convective supercells. In addition, using POVP guided R(Z) relationship shows significant improvement on radar QPE compared with the traditional Z-R relationships. Lastly, the Hydrometeor Classification Algorithm is merged with POVP within the core of convection and show new insights into convective microphysics and matched with surface hail reports. Tangible outcomes from this project include 1 formal journal articles, 2 conference presentations, and 1 algorithm ready for transition to NWS operations.

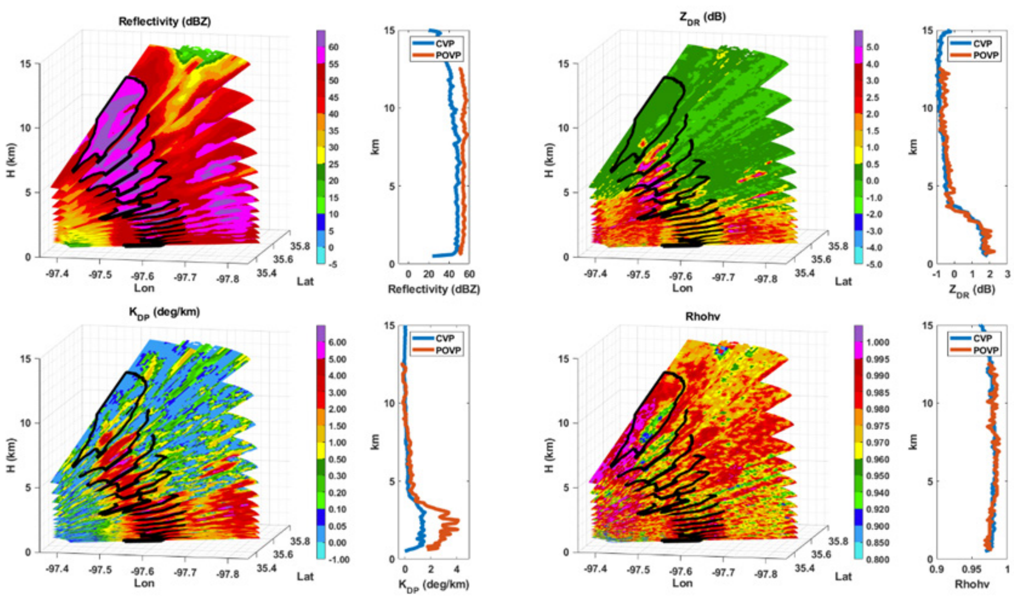


Figure 2-34: 3D demonstration of the POVP technique (black contour) using all available PPI scans. Each panel consists of the 3D PPI view of the supercell shown in Figure 4 and the vertical profile comparison of both CVP and POVP techniques. (a) Reflectivity, (b) ZDR, (c) KDP, and (d) ρ_{hv}.

CIWRO Themes: Weather Radar and Observations
CIWRO Contributor: Edwin Dunnavan
Project Title: Improving understanding of ice particle shapes and orientations: Reconciling 2D-S cloud probe observations with theoretical simulations
Relevance to NOAA: This project supports the NOAA mission by optimizing platform-agnostic data and information and by creating/improving a trusted analysis of record for model verification/nowcasting.

Ellipsoids are very commonly used as geometric proxies when simulating polarimetric radar variables in many scattering models and radar retrieval algorithms. However, there are still large uncertainties regarding what ellipsoidal shapes and effective densities should be used in such algorithms and models. This project utilizes over 14 million Two-Dimensional Stereo (2D-S) particle images from 26 in-situ aircraft cases from the NASA IMPACTS field campaign to estimate such 3D ellipsoid parameters of stratiform ice particles. Each 2D-S particle image from the instrument's horizontal and vertical channel are fitted with best-fit ellipses and 3D ellipsoidal characteristics are inferred by performing various simulations using both idealized triaxial ellipsoid shapes as well as STL models of realistic ice particle habit types. This project is being conducted with external collaborators from NASA Goddard, the University of North Dakota, and UCAR/NCAR and has resulted in 1 conference presentation.

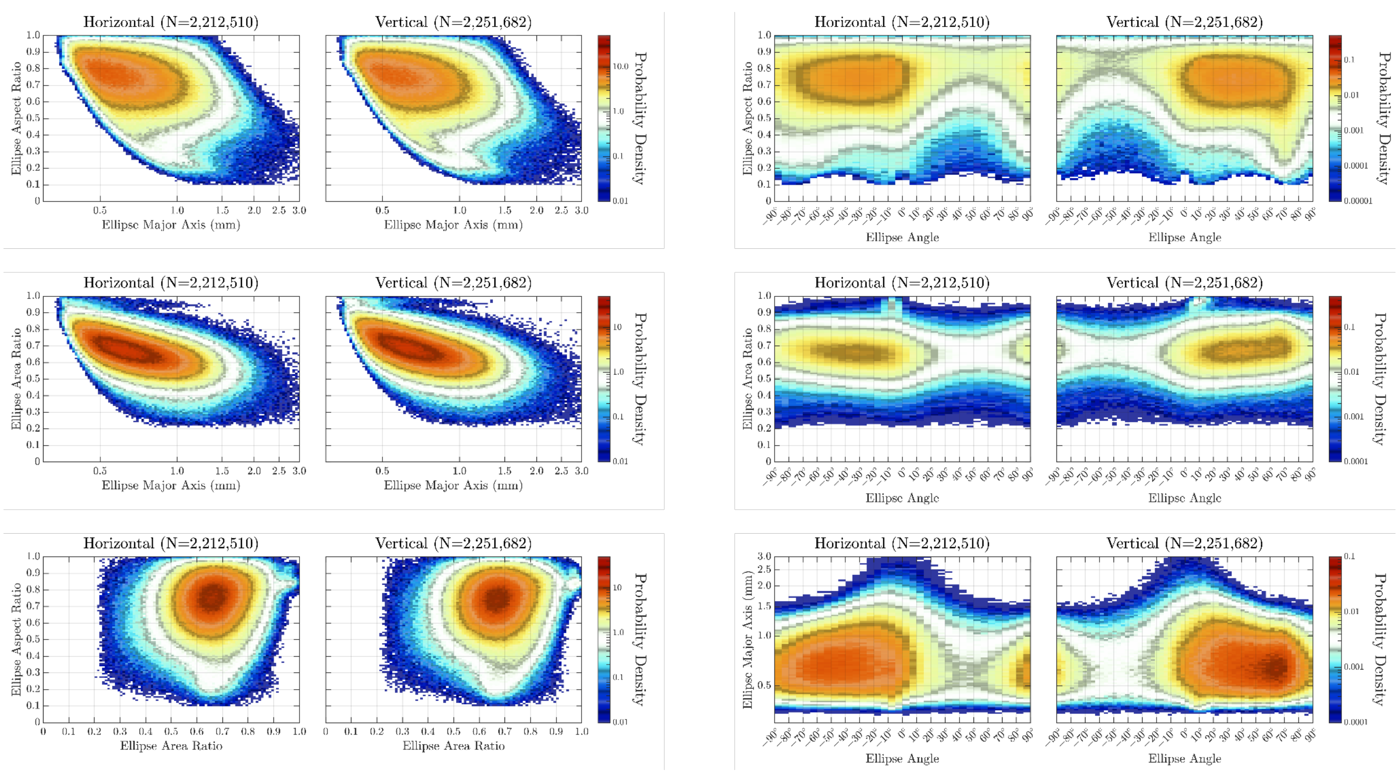


Figure 2-35: Joint distributions of ellipse-fit ice particle parameters from 8 cases of the NASA IMPACTS field campaign from the 2D-S horizontal and vertical channels.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Jiaxi Hu, Edwin Dunnavan, Alexander Ryzhkov
Project Title: Dual polarimetric radar analysis
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions

This study leverages polarimetric radar data to analyze snow microphysics and cloud ice properties across various meteorological systems. Using dual-polarization radar techniques, vertical profiles of radar reflectivity (Z), differential reflectivity (Z_{DR}), specific differential phase (K_{DP}), ice water content (IWC), liquid water content (LWC), mean volume diameter (Dm), and total number concentration (Nt) are derived. For 25 synoptic snow (SS) and 23 lake-effect snow (LES) cases, SS profiles show linear Z increases with dendritic growth layer peaks in Z_{DR} and K_{DP}, while LES profiles exhibit negative Z_{DR}, high Z, negligible K_{DP}, and conical graupel influences. Additionally, 34 mesoscale convective systems (MCSs) and tropical cyclones are analyzed, revealing continental MCSs have larger, less concentrated ice particles aloft than marine MCSs and tropical cyclones. Aggregation efficiencies in SS and high IWC in convective systems provide insights for numerical weather prediction and improve model representations of snowfall and cloud ice processes. Tangible outcomes from this project include 2 formal journal articles, 3 conference presentations.

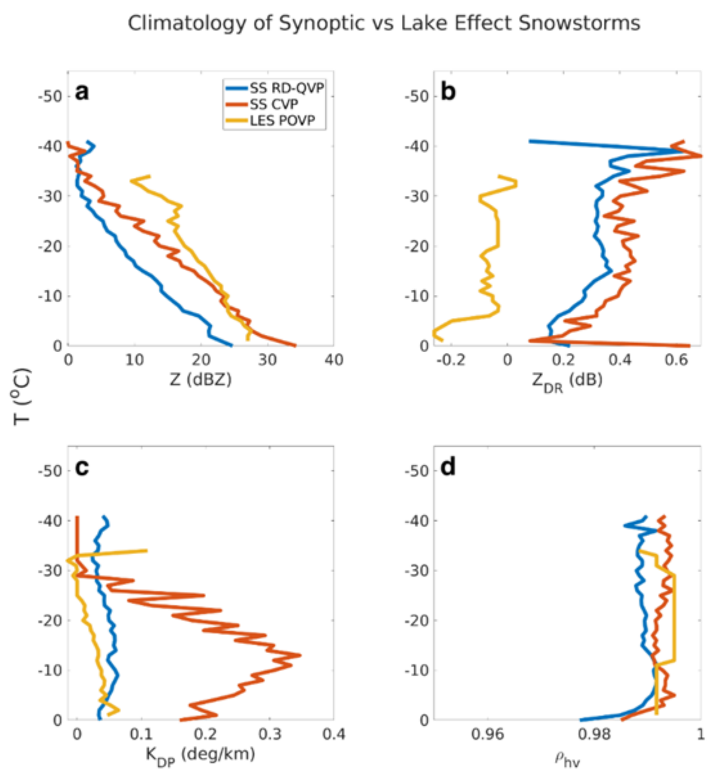


Figure 2-36: Median vertical profiles for the lake effect snow band using POVP (yellow), synoptic snow background state using RD-QVP (blue), and synoptic snow HIWC using CVP (orange) datasets: (a) Z, (b) Z_{DR}, (c) K_{DP}, and (d) ρ_{hv}.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Kristofer Tuftedal, Charles Kuster, Terry Schuur
Project Title: Radar signatures associated with quasi-linear convective system mesovortices
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

Our understanding of quasi-linear convective systems (QLCSs) has been rather limited until recently. While analyses of conventional dish radar data has allowed us to glean some insight into these storms and their processes, the slow volume update time substantially limits our ability to observe how any identified signatures evolve over time, especially for rapidly evolving features. To address this issue, we have leveraged the Advanced Technology Demonstrator (ATD) phased-array radar (PAR) to investigate QLCSs in more temporal detail and compared these analyses to those derived from the KTLX and/or KOUN WSR-88D radars. We have found that specific differential phase (K_{DP}) cores (a known precursor to severe winds at the surface; Kuster et al. 2021) can collapse or change in intensity quickly enough that these events may occur in-between WSR-88D scans, potentially resulting in unwarned severe wind events or delayed identification of areas of concern. Work done by an undergraduate student in the OU Research Experience for Undergraduates (REU) program highlighted this temporal difference well and showed that K_{DP} core collapse may happen south/southwest of where an eventual mesocyclone will form, resulting from the surge of wind generating cyclonic vorticity north/northeast of these collapses along the periphery of the severe wind surge. This project has supported one summer REU student and has resulted in five conference presentations.

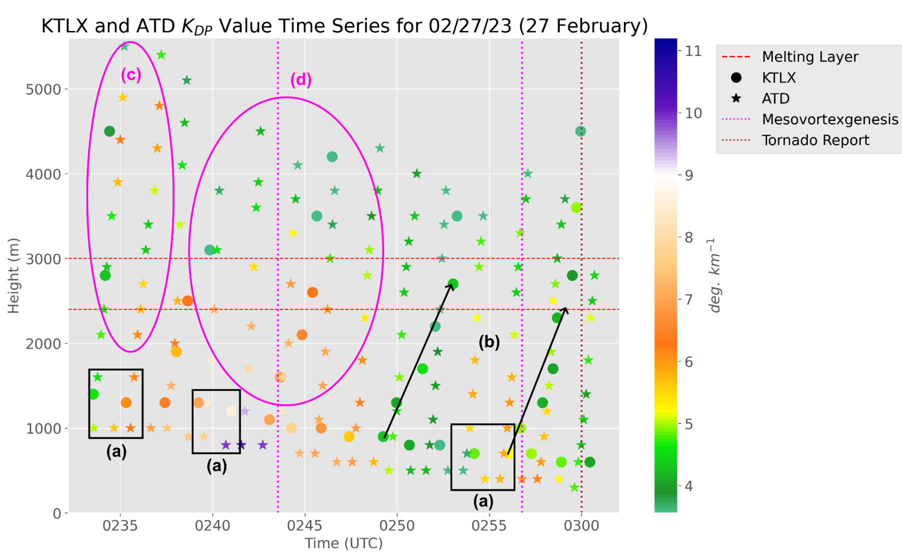


Figure 2-37: Time series of maximum K_{DP} value (colors) wrt height above radar level from on 27 February 2023. Star (circle) shaped markers denote K_{DP} values from ATD (KTLX). The bottom/top of the melting layer is denoted by the horizontal dashed red lines. Time of mesovortex genesis is represented by vertical dashed pink lines. Tornado report times are shown as a vertical dashed brown line. The annotations on the plot represent (a) sharp increases in K_{DP}, (b) KTLX volume scans missing a substantial fluctuation in K_{DP} seen in ATD, (c) a vertically discontinuous K_{DP} column, and (d) a vertically continuous K_{DP} column.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributor: Alexander Ryzhkov
Project Title: Improving storm-based hail size estimation using non-local polarimetric signatures.
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds and developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

Polarimetric signatures of hail in the upper parts of hailstorms are indicative of hail size observed at the service. These are directly or indirectly related to hail formation. Large hail grows in convective updrafts, which are commonly manifested by the differential reflectivity (Z_{DR}) columns. The vertical extension of the Z_{DR} column and its width characterize the updraft intensity and residence time for hail embryos to grow. Additional polarimetric radar signatures within the updraft that indicate very large or giant hail include negative values of Z_{DR} above the top of the Z_{DR} columns associated with extremely low magnitudes of the cross-correlation coefficient ρ_{hv}. Negative values of Z_{DR} at S band can be explained by the presence of hailstones with sizes exceeding 5 – 6 cm that exhibit resonance scattering. A systematic study of hailstorms producing reported hail larger than 12 cm in diameter shows that maximum hail size is best correlated with minimum ρ_{hv} and minimum Z_{DR} at -30°C. Both of them are more strongly correlated with hail size than is mid-altitude rotational velocity (MRV), storm-top divergence (STD), and such correlation is much stronger than the one of the traditional Z-based Maximum Estimated Size of Hail (MESH).

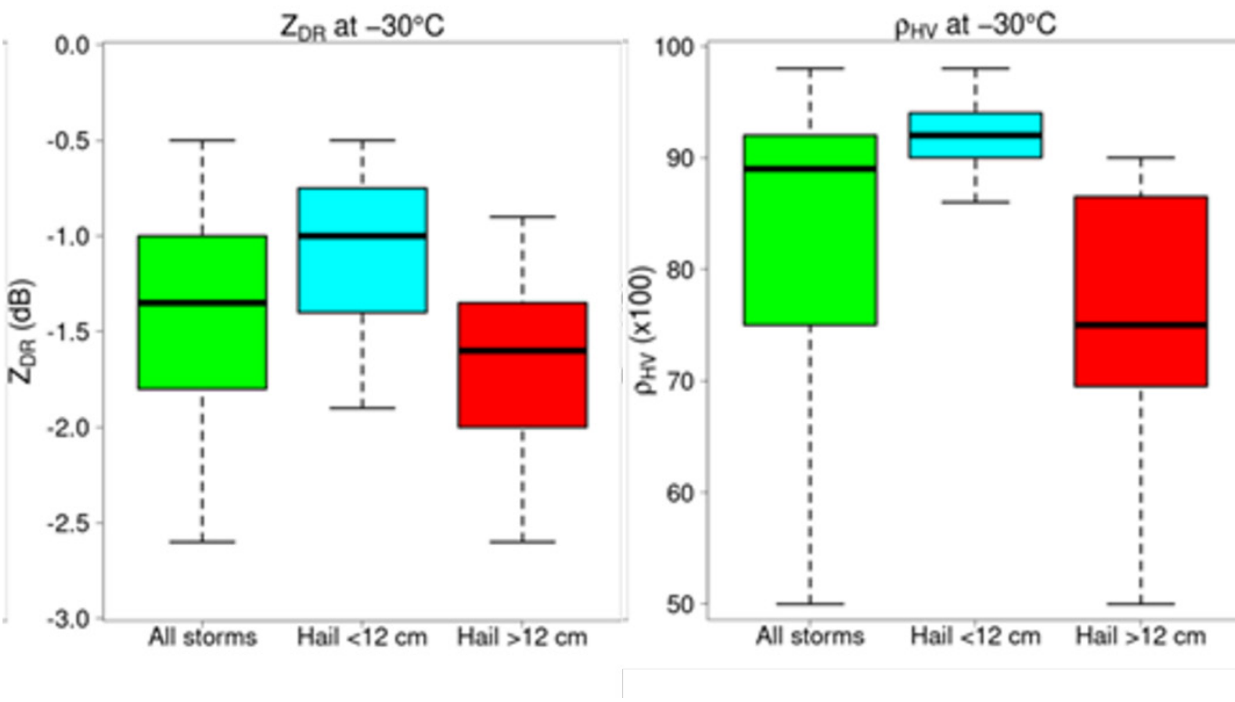


Figure 2-38: Distributions of Z_{DR} and ρ_{hv} at -30°C for all hailstorms and storms producing hail larger or smaller than 12 cm.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Alexander Ryzhkov, Jiaxi Hu, Savannah Southward
Project Title: Using polarimetric radar observations, cloud modeling, and in situ aircraft measurements for large hail detection and warning of impending hail
Relevance to NOAA: Enhancing capabilities for the Radar Next program and/or WSR-88Ds. Developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events

Advanced polarimetric weather radars are the best instruments to remotely detect hail in the clouds, estimate its size, and produce timely warnings of impending hail if guided by the physical cloud models that predict hail growth and its fallout on the surface. This project capitalizes on the unique observations of hail from the armored T-28 research aircraft that penetrated hail-bearing storms during multiple field campaigns in the past. Combining direct hail measurements within the cloud aloft and at the surface with cloud modeling describing its evolution on the way to the ground and the collocated polarimetric radar observations within the full depth of the storm will help to better understand the microphysical processes of hail generation and develop more advanced methodologies for its quantification and prediction / nowcasting. This is a collaborative project with NCAR, which examines and provides T-28 aircraft data. This data will be used to initialize the spectral bin cloud model of melting hail developed at CIWRO which describes the evolution of hailstones as they fall to the surface and generates the associated vertical profiles of polarimetric radar variables. This will allow to retrieve size distribution of hail above the melting layer using vertical profiles of radar variables associated with melting hail within the melting layer and beneath and will serve as an observational reference for cloud models' evaluation and optimization.

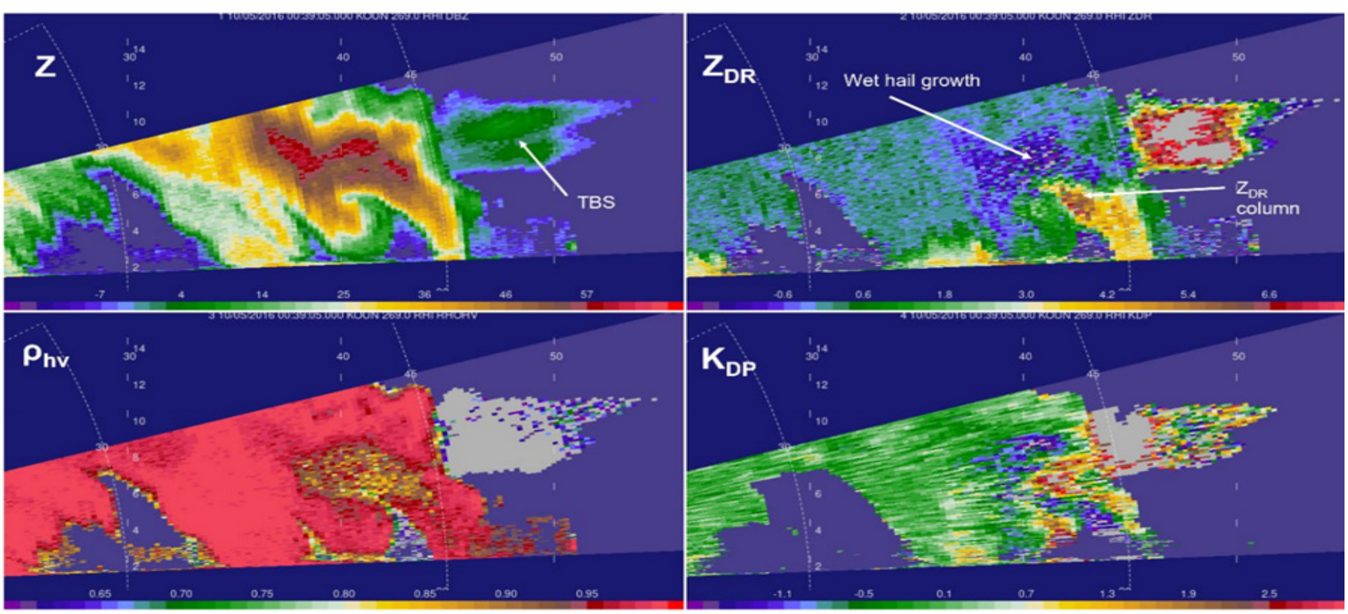


Figure 2-39: Composite RHI of Z, Z_{DR}, K_{DP}, and ρ_{hv} measured by the KOUN WSR-88D radar during the storm producing very large hail on 5 October 2016. The areas of wet growth of hail, Z_{DR} column, and three-body scattering (TBS) signature are shown by the arrows.

CIWRO Themes: Weather Radar and Observations, Mesoscale and Stormscale Modeling, Forecast Application Improvements
CIWRO Contributors: Ben Schenkel, Thea Sandmæl, Kayla Wheeler, Reagan Mendeke, Sadie Mullinix, Dzuy Nguyen, Roy Galang
Project Title: Increased understanding of tropical cyclone tornado occurrence and evaluation of their associated forecast skill
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions

This project has two foci: 1) basic research identifying the factors driving variability in the number of tornadoes among tropical cyclones with similar characteristics and 2) applied research quantifying tropical cyclone tornado warning skill and the utility of products used in making these forecasts. The first part of this project has focused on investigating the characteristics of the tropical cyclone and its synoptic-scale environment in driving variability in tornado frequency. This work, thus far, has found that increasing synoptic-scale baroclinity is associated with greater numbers of tornadoes, especially strong ones, that become strongly localized in the eastern sector of the tropical cyclone as suggested in the figure below (Wheeler et al. 2025). The second portion of this work entails developing the first data on tropical cyclone tornado warning forecast skill and which products, if any, may be useful improving this skill. This work has also shown that the Warn-on-Forecast System is able to reasonably simulate those convective-scale environments in tropical cyclones (Schenkel et al. 2024). Project outcomes include four formal journal articles (one in review), 10 conference presentations, one GRA supervised, one Hollings student mentored, and one funded NSF proposal. External partners involved in this project include NWS/SPC, OAR/NSSL, and OU/SoM.

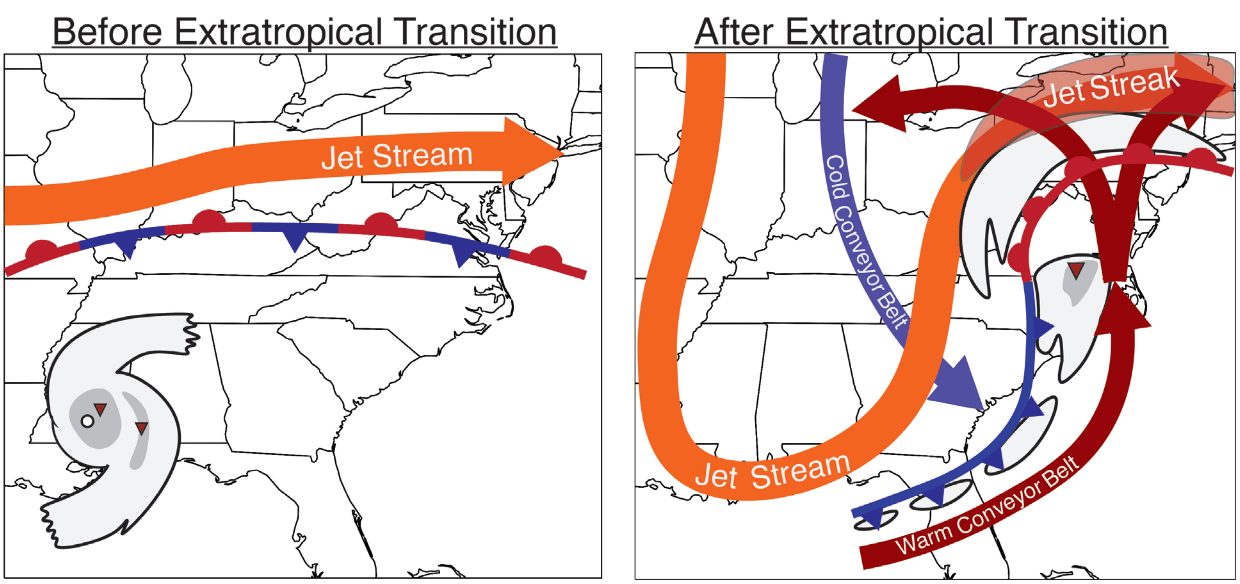


Figure 2-40: Summary schematic showing the horizontal structure of tropical cyclones and their associated tornadoes (left) before and (right) after extratropical transition (e.g., Wheeler et al. 2025).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributor: Cameron Nixon
Project Title: Boundaries, cell mergers, and convective systems in cases of significant tornadoes and hail
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions, and developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

This project sought to understand why, out of multiple supercells in similar background environments, some produce tornadoes and/or large hail while others don't. We found using WSR-88D data that regardless of the background environment, tornadic supercells tended to be accompanied by other cells in their rear flanks and free of cells in their forward flanks (Nixon et al., 2024). Tornadic storms had more rear-flank cells than non-tornadic storms 30 minutes before tornadogenesis, suggesting that storm interactions may add important information beyond the current average tornado warning lead time. In addition to tornadoes, we found that hailstorms were commonly accompanied by fine-line boundary signatures, and most often on the cool side of the boundary. Tangible outcomes for this project included 1 journal paper, 2 conference presentations, and a training course given to several NWS Weather Forecast Offices. This work also initiated new projects and ongoing collaborations with 3 undergraduate students and 3 master's students from 5 universities. This project was performed in collaboration with NCEP/SPC and Central Michigan University.

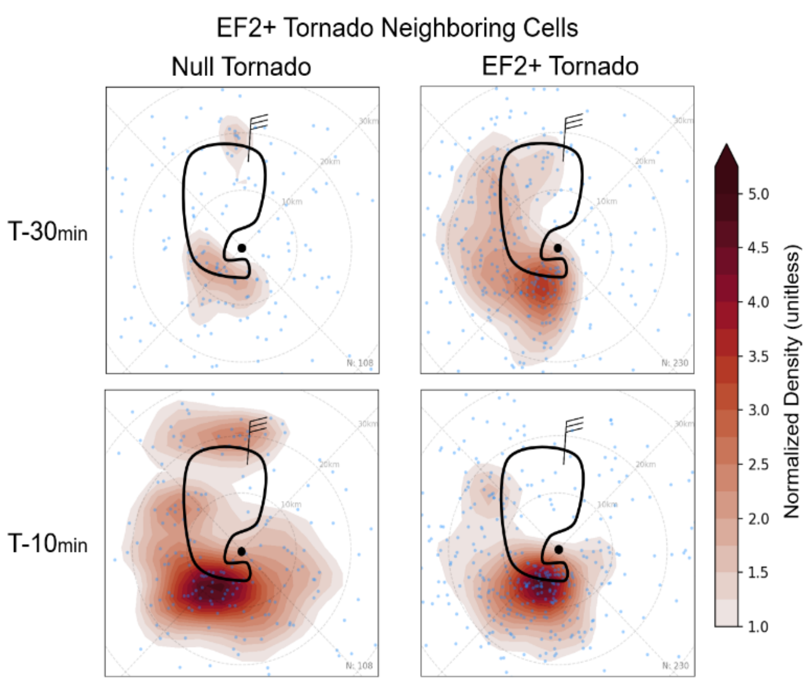


Figure 2-41: Positions of the centroids of all external cells (in a rotated, storm-relative sense) noted near supercells in this study, their densities shaded in red. Tornadic cells were accompanied by more cells in their rear-flanks at longer lead times, and fewer cells in their forward flanks at shorter lead times, than non-tornadic storms.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Martin Satrio, Madeline Diedrichsen
Project Title: Cell mergers with supercells and their association with mesocyclone evolution
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions, enhancing capabilities for the Radar Next program and/or WSR-88Ds, and developing reliable probabilistic guidance products.

A cell merger database was created by manually analyzing the evolution of 342 right-moving supercells using observed WSR-88D radar data and the Multi-Year Reanalysis of Remotely Sensed Storms (MYRORRS) dataset. Information of mergers, or lack thereof, for each supercell were recorded for the entire lifetime of the supercell that occurred within 100 km of a WSR-88D radar. Then the maximum azimuthal shear at each point of the supercell track was also recorded to determine the low-level mesocyclone strength changes over time. The cell merger database showed that nearly one-half of supercells in the dataset experienced at least one cell merger, but the strength of the supercell was not related to whether cell mergers occurred. Cell mergers were found to influence changes in azimuthal shear from before to after the merger event. An inverse relationship was found between the magnitude of premerger azimuthal shear and the change in azimuthal shear during the merger event. Therefore, cell mergers likely impact supercell mesocyclone strength, though the occurrence of a merger event is more likely attributed to the environment and large-scale setup than supercell impacts. The comprehensive cell merger database created during this study has helped to establish a baseline dataset for subsequent cell merger studies (Lyza and Flournoy 2023; Fischer et al. 2023; Flournoy et al. 2024). This project resulted in one published journal paper and one conference presentation.

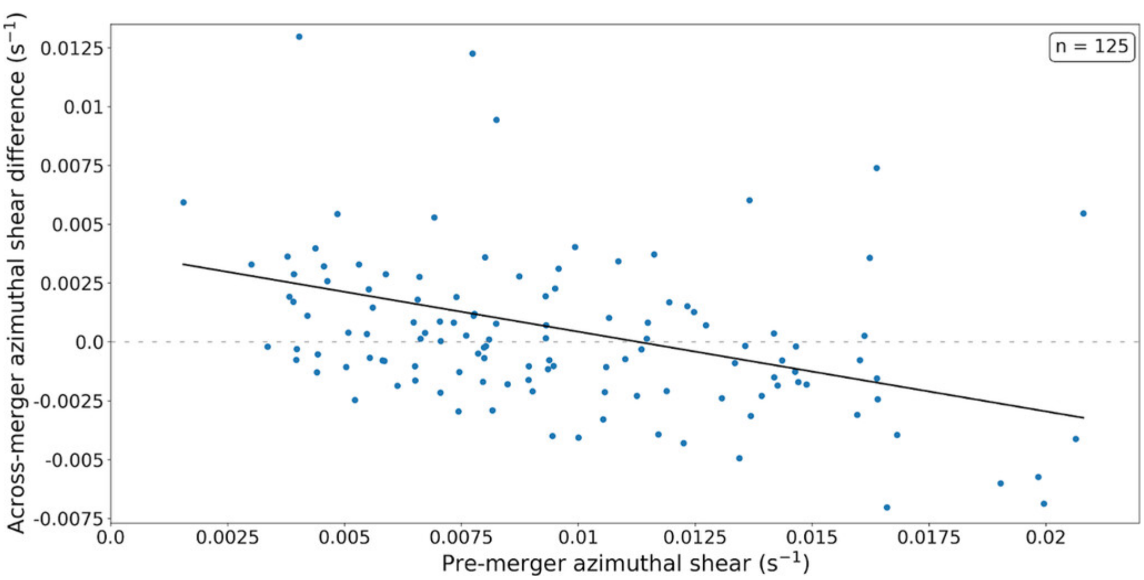


Figure 2-42: Scatterplot of 125 supercells that experienced at least one merger event showing the change in azimuthal shear across the merger event for different supercell low-level mesocyclone strengths. The statistically significant best fit line is shown. Two outliers with premerger azimuthal shear > 0.03 s−1 are omitted from this analysis.

CIWRO Themes: Weather Radar and Observations, Mesoscale and Stormscale Modeling
CIWRO Contributor: Lauren Pounds
Project Title: Analysis of hail production and hail model sensitivity via simulated hailstone trajectories
Relevance to NOAA: This project supports the NOAA mission by developing a next-generation hail modeling framework by adding novel improvements to existing hail models and furthering our understanding of hail processes.

Pounds et al. (2024) shows the findings from hundreds of thousands of hailstone trajectories. Rather than using model fields to generate hailstone trajectories, radar observations (multi-Doppler analyses) and Diabatic Lagrangian analyses (DLA) were used. It was found that the largest hailstones reside within the downshear deacceleration zone (DDZ) where the hailsone and the updraft are in balance and residence time can be extended. In efforts to improve the hail model, Pounds et al. (2025) (in internal review) performed multiple sensitivity analyses. The sensitivity analyses showed oblate hailstones are closer to reality than spherical hailstones (which most hail models use). This work has resulted in two conference presentations and one journal article with another journal article in the works.

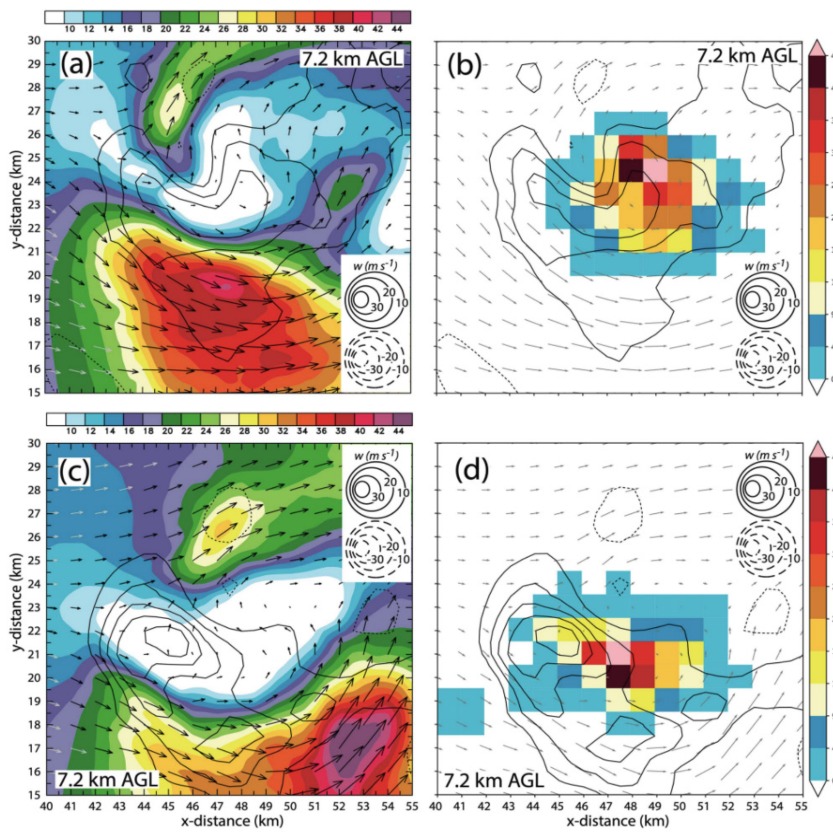


Figure 2-43: Horizontal and vertical air speeds relative to severe hail concentrations at 7.2 km AGL at (a),(b) 2315 and (c),(d) 2345 UTC. (left) Horizontal wind speed exceeding 10 m/s and (right) column-integrated severe hail concentration. Black contours (solid 5 positive, dotted 5 negative) are vertical velocity (m/s) with contour levels indicated by the inset. Vectors are storm-relative horizontal airflow.

CIWRO Themes: Weather Radar and Observations, Mesoscale and Stormscale Modeling
CIWRO Contributor: Morgan Schneider
Project Title: Mesovortex evolution in a simulated QLCS-supercell merger
Relevance to NOAA: This project supports the NOAA mission by using simulations to improve the understanding and prediction of storm evolution during squall line-supercell mergers.

Mergers between squall lines and supercells have been linked to the formation and intensification of mesovortices, but few studies have sought to address the dynamics of these interactions. In this work, idealized simulations are used to study the evolution of rotation in a mesovortex during a squall line-supercell merger. The rotation that develops from the remnant supercell mesocyclone is stronger, deeper, and more persistent than rotation in a non-merging squall line, suggesting that the merger enhances rotation intensification, and that the mesovortex retains some of its supercellular characteristics. Trajectory analysis reveals that air from the environment cycles through a strong downdraft before entering the mesovortex, but that mechanisms for rotation generation vary over the course of the merger. Storm features and structures typically seen in either supercells or squall lines are both present in the merger mesovortex, implying that mesovortices in squall line-supercell mergers may be characterized by a combination of both supercell-like and squall line-like processes. This project is ongoing and has resulted in one manuscript currently being written and one conference presentation.

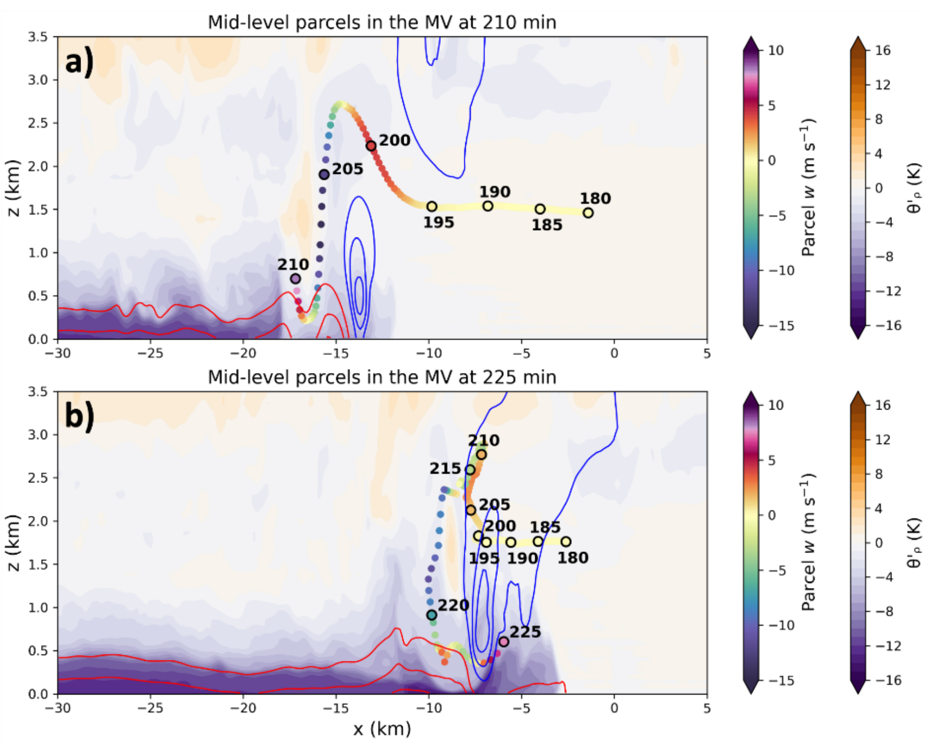


Figure 2-44: Vertical cross sections of potential temperature perturbation (shaded) and pressure perturbation (contoured every 1 hPa, with red denoting positive and blue denoting negative perturbations) at times (a) just before the merger and (b) after the merger, with select median air trajectories overlaid (colored by vertical wind speed). Time is annotated every 5 min along the trajectories.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Yixin Wen, Terry Schuur
Project Title: Catalogue comparing NOAA's ground-based weather radar and NASA-JAXA's spaceborne radar
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

The National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) have a long and successful history of weather radar research. The NOAA ground-based radars—WSR-88D network—provide nationwide precipitation observations and estimates with advanced polarimetric capability. As a counterpart, the NASA–JAXA spaceborne radar—the Global Precipitation Measurement Dual-Frequency Precipitation Radar (GPM DPR)—has global coverage and higher vertical resolution than ground-based radars. While significant advances from both NOAA's WSR-88D network and NASA–JAXA's spaceborne radar DPR have been made, no systematic comparisons between the WSR-88D network and the DPR had ever been done. This project generated nationwide comprehensive comparisons at 136 WSR-88D radar sites from 2014 to 2020. Systematic differences in reflectivity were found, with ground radar reflectivity on average 2.4 dB smaller than that of the DPR (DPR version 6). This research found the discrepancies between WSR-88D and DPR arise from different calibration standards, signal attenuation correction, and differences in the ground and spaceborne scattering volumes. The project resulted in 1 formal journal article.

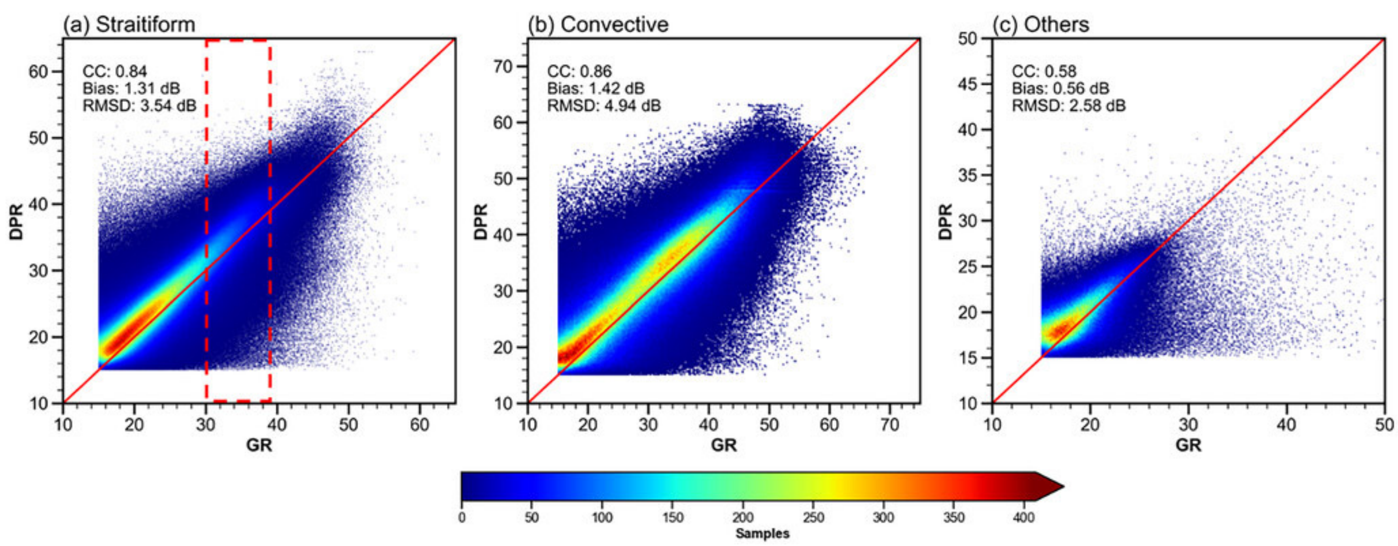


Figure 2-45: WSR-88D and DPR reflectivity comparisons by precipitation types for (a) stratiform precipitation, (b) convective precipitation, and (c) others. The red dashed rectangle in (a) highlights the region where the high-density samples start to deviate from the 1:1 line.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Patrick Servello, Allen Zahrai, Noah Zemlin
Project Title: ATD computing infrastructure upgrade
Relevance to NOAA: This project supports the NOAA mission by developing next-generation observational capabilities

In this project, the computing infrastructure of the Advanced Technology Demonstrator (ATD) was upgraded to enhance system longevity and increase computational performance, enabling the exploration of more complex operational modes. The upgrades were completed ahead of schedule and included the acquisition, configuration, installation, and migration of 29 new servers to a supported operating system. Additional hardware improvements consisted of 2 high-speed network switches, 1 network infrastructure bottleneck enhancement, and 1 precision timekeeping device. This project also resulted in the creation of the first comprehensive draft document detailing the configuration and setup of the radar server infrastructure.

Photo 2-2: New computing infrastructure installed inside of the ATD

CIWRO Theme: Weather Radar and Observations
CIWRO Contributor: Noah Zemlin
Project Title: ATD system readiness & health monitoring
Relevance to NOAA: This project supports the NOAA mission by developing next-generation observational capabilities

In this project, new tools and automated monitoring services were developed to enhance the safety and simplicity of operating the Advanced Technology Demonstrator (ATD). These tools replaced the manual interpretation of diagnostic data by engineers to identify hardware subsystem errors and determine radar operational status. The new tools deliver near-instant feedback to radar operators on potential performance issues, eliminating the need for active engineering support during operations. Tangible outcomes from this project include 8 new software tools comprising 844 lines of code.

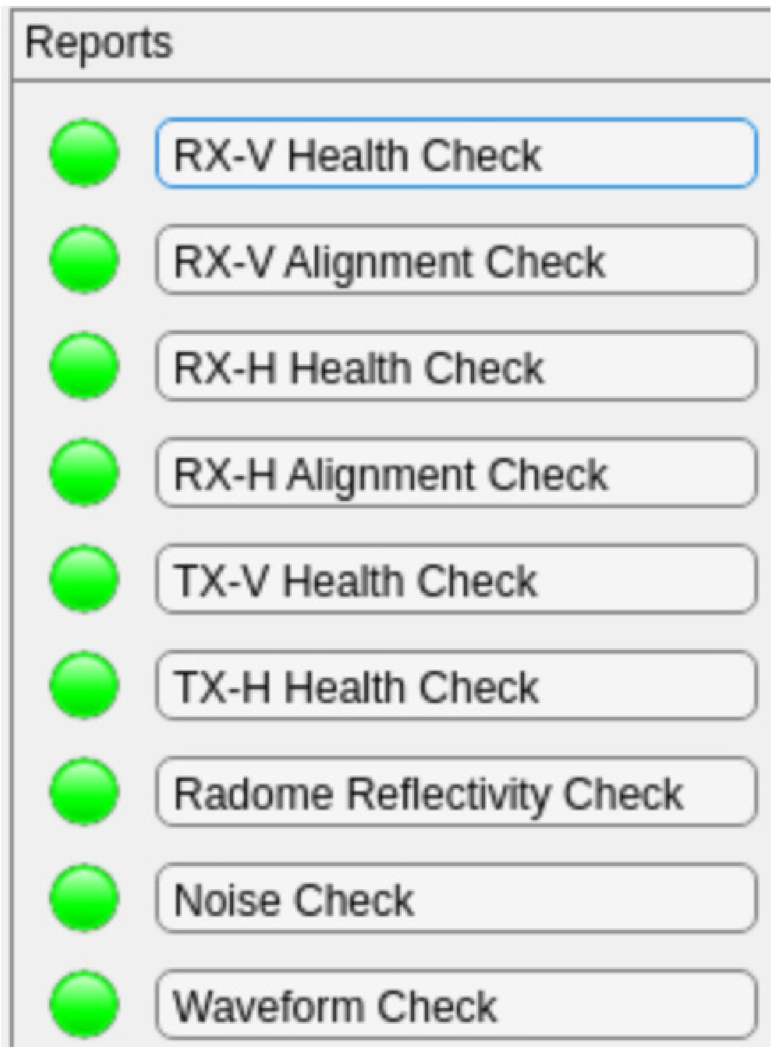


Figure 2-46: Screenshot showing the status view which tells operators if the radar is ready to use

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Noah Boeckman, Christopher Curtis, Robert Estes, Eddie Forren, Stephen Gregg, Rakshith Jagannath, Feng Nai, Sebastián Torres
Project Title: Application software for the ATD
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

The Advanced Technology Demonstrator (ATD) advances NOAA's PAR R&D program by showcasing the unique capabilities of polarimetric phased-array technology for weather observation. The ATD supports both engineering and meteorological research, with its advanced scanning capabilities continually being enhanced. CIWRO developed essential application software for the ATD, enabling functions such as digital signal processing, adaptive scan control, system monitoring, calibration, and data archiving. The system operates in real time, processing up to 3.3 GB of data per second across a distributed infrastructure of 500+ processes running on 14 servers. Additionally, a separate 11-server system is used for software development and testing. Since its operational launch in October 2021, the ATD software has supported radar operations, with over 120 data cases collected and two major software releases per year. The project's accomplishments include completing a major server upgrade, conducting 250+ eight-hour end-to-end tests (~2000 hours of testing) to assess system performance and stability, and providing real-time software support to maximize data collection efficiency. Key updates also included improving memory management in the real-time digital signal processor and enhancing user interfaces in the user interface for advanced scanning strategies. Tangible outcomes include 7 major software releases that continue to improve the ATD's capabilities for weather radar research.

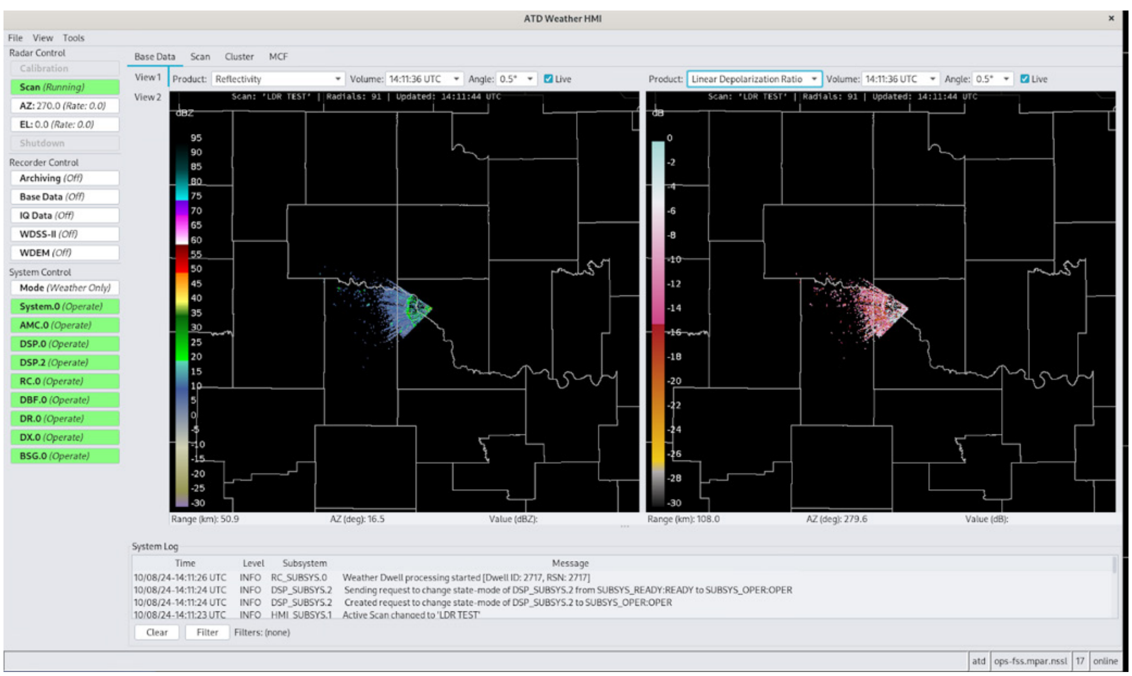


Figure 2-47: User interface that allows control and monitoring of weather scanning with the ATD.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Christopher Curtis, Robert Estes, Igor Ivić, Rakshith Jagannath, Feng Nai, Sebastián Torres, David Warde
Project Title: Data quality improvements for the ATD
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

This project focuses on the ongoing development and enhancement of techniques and tools to improve data quality from the Advanced Technology Demonstrator (ATD) phased-array radar. The ATD is a key asset for engineering and meteorological research at NSSL and is expected to support radar technology and weather observation studies for years to come. A primary goal of this project is to refine existing signal processing techniques, such as velocity dealiasing, to ensure accurate weather measurements under various operating conditions. The project also addresses troubleshooting and resolving data quality issues that arise during routine operations, ensuring that the ATD maintains high performance throughout its operational life. By identifying and addressing these issues, the project contributes valuable insights to the field of phased-array radar development, benefiting the design of future radar systems. Accomplishments include improving both Dual-PRF and Triple-PRF Doppler velocity dealiasing algorithms to recover more data and reduce velocity dealiasing errors, updating the MATLAB Digital Signal Processing (DSP) for improved code usability and readability, studying time series data to identify potential hardware issues, and updating the DSP to address signal processing concerns raised by meteorologists during or after data collection. These efforts ensure that the ATD remains a reliable and advanced tool for engineering and meteorological research. Tangible outcomes include improvements and updates to several DSP software features and enhancing the ATD's ability to support weather radar research.

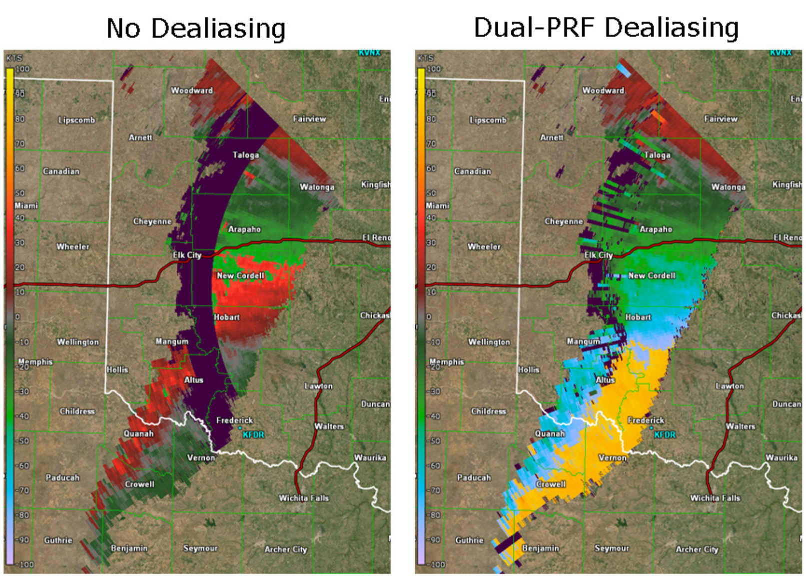


Figure 2-48: The left panel shows dual-PRF Doppler velocity data with no velocity dealiasing; the right panel shows the same data after the 1D Dual-PRF velocity dealiasing algorithm was applied.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Igor Ivić, Rakshith Jagannath, Feng Nai, Sebastián Torres
Project Title: Polarimetric calibration of PAR
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

This project addresses challenges in polarimetric PAR systems, particularly related to accounting for the effects of antenna patterns that lead to bias in radar variable estimates. Unlike parabolic antennas, polarimetric PARs experience cross-coupling between horizontally and vertically polarized fields, which results in polarimetric measurement errors (Ivić 2023). Additionally, scan-dependent biases, known as beamsteering biases, arise due to variations in antenna patterns as the radar beam is steered. The project focuses on identifying and correcting these biases on the Advanced Technology Demonstrator ATD) by measuring copolar and cross-polar antenna patterns at various steering angles. Data are collected using a calibration tower to generate correction factors for key radar variables such as reflectivity, differential reflectivity, and differential phase. The project also collaborates with the OU Advanced Radar Research Center (ARRC) to use UAS for improved measurement accuracy and speed. Another aspect of the work involves developing methods to reduce cross-coupling biases, which remain challenging at certain steering angles. The ultimate goal is the development of a robust polarimetric calibration process for operational PAR systems, enabling them to produce data of comparable quality to traditional parabolic radar systems. Key accomplishments include the development of calibration procedures using the ATD calibration tower, successful demonstrations of polarimetric calibration effectiveness, and the development and testing of procedures to use UAS for antenna pattern measurements. Additionally, the project explored pulse-to-pulse phase coding to mitigate cross-coupling contamination (Ivić 2002) and demonstrated its success in reducing radar variable biases. Tangible outcomes include 2 journal papers, 5 conference presentations, and 1 NSSL technical report.

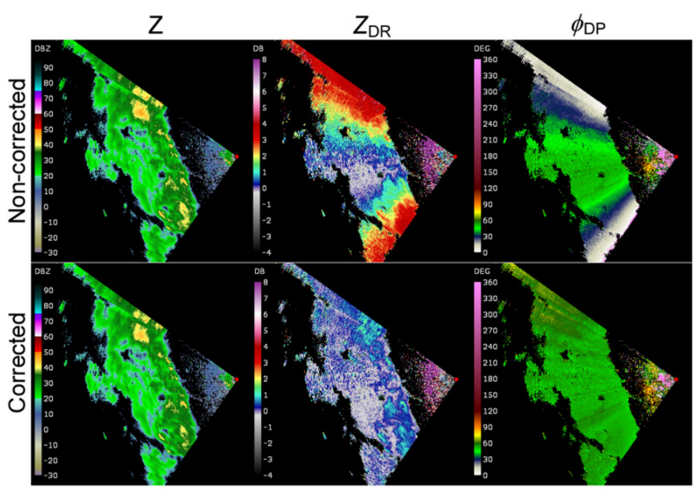


Figure 2-49: Non-calibrated (top row) and calibrated (bottom row) reflectivity, differential reflectivity, and differential phase. Without applying the correction factors produced by the calibration process, radar fields showed significant bias as beams are steered towards the edge of the scanning sector.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributor: Djordje Mirkovic
Project Title: Polarimetric phased array antennas performance
Relevance to NOAA: Developing next-generation observational capabilities and enhancing capabilities for the Radar Next program and/or WSR-88Ds

This project focuses on the importance of calibration on phased-array radar (PAR) systems and the implications of antenna characteristics on the quality of polarimetric data. We used computational electromagnetic modeling (CEM) to accurately calculate radiation properties, evaluate antenna array approximations, and compare various antenna geometries to determine the most effective solution for minimizing biases in the radar data. Furthermore, we investigated the effect of antenna modeling approximation to determine the approximation effect on the accuracy of model predictions. This research will provide valuable insights for NOAA in defining requirements for future radar systems, by understanding antenna limitations and determining the applicability of approximations polarimetric-data bias calculations. Furthermore, our study on array element input impedance will allow for a better understanding of how beam steering angles affect radiation characteristics, motivating the implementation of adaptive beam weighting for improved performance. Through this research, we aim to contribute to the advancement of radar technology and provide critical information for the development of a more accurate and reliable weather radar system. The project resulted in two journal publications, one book chapter, and three conference presentations.

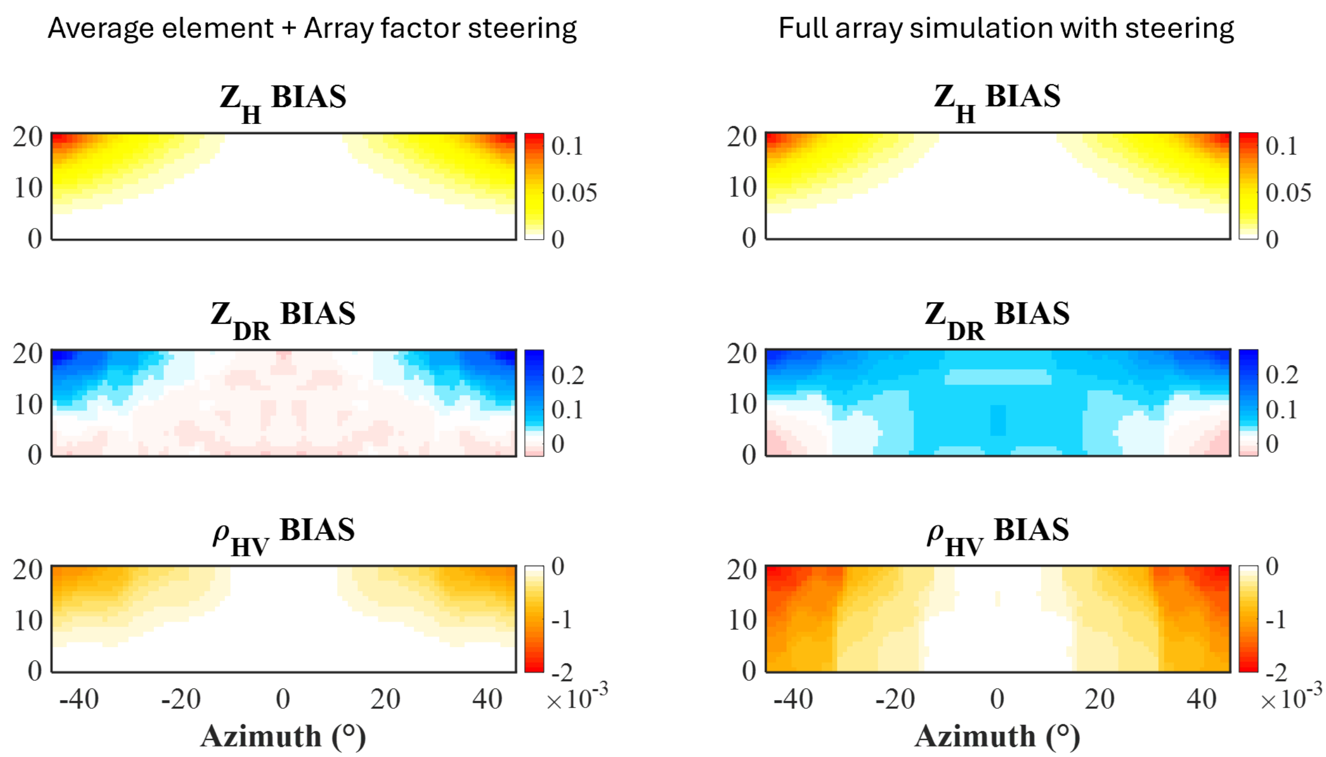


Figure 2-50: A comparison of polarimetric biases was calculated using two techniques. Left - the derived representative antenna element; Right - the whole array.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributor: Djordje Mirkovic
Project Title: Computational electromagnetic research of fully digital arrays
Relevance to NOAA: Developing next-generation observational capabilities and enhancing capabilities for the Radar Next program and/or WSR-88Ds

This project focuses on applying Computational Electromagnetic (CEM) modeling to very large arrays. For example, we modeled a 16-panel array with 64 radiating elements per panel and determined its radiation characteristics. Modeling of these array sizes has never been conducted and the results were compared with pre-modeled smaller array sizes. Performance was assessed in terms of the polarimetric bias calculations, which are part of another study. An important outcome of this study is a novel algorithm that was modified from its original purpose to allow for the recalculation of beam-steering radiation patterns from the simulation of the full array in One Generator at Time mode (OGAT). This has enabled us to conduct precise full 3D CEM simulations of all beam steering directions by postprocessing the OGAT simulation data, resulting in significant time savings. This project involved 2 undergraduate and 1 graduate students.

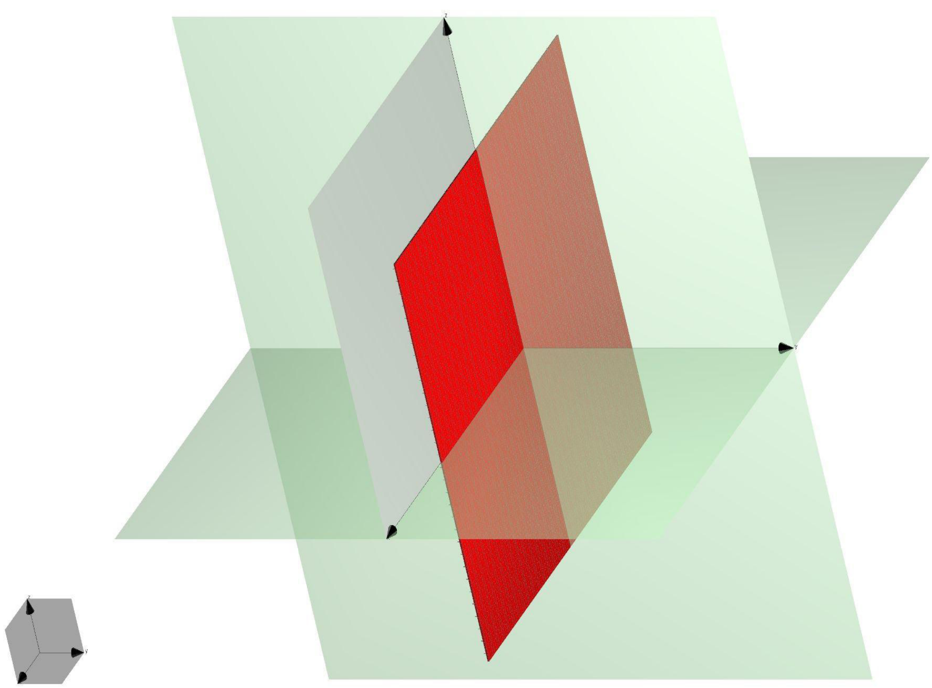


Figure 2-51: Model of the 16-panel array showing advanced simulation techniques using (A)symmetry of the model. (A)symmetry is the advanced option allowing for modeling of very large structures with geometrical symmetry of object without assuming symmetry of excitations.

CIWRO Theme: Weather Radar Observations
CIWRO Contributor: Antonio Segales
Project Title: Demonstrating applications for science and engineering of a fully digital phased array weather radar
Relevance to NOAA: This project supports the NOAA mission by developing next generation observational capabilities.

The WSR-88D network is nearing end-of-life, and NOAA is exploring replacement options, including phased array radar—a long-time focus of the Advanced Radar Research Center (ARRC). With NSSL funding, ARRC recently completed Horus, a fully digital, polarimetric S-band phased array radar mounted on a truck for mobility. This project has led to key research areas, including UAS-based calibration for fielded radar systems. Reliable calibration remains a challenge for Phased Array Radars (PARs), and UAS-based systems offer a cost-effective solution. This work has produced the first UAS-based 3D radiation patterns for Horus and ATD radars and developed the RFSonde, a custom UAS designed for precise in-flight antenna measurements. Equipped with a gimbal control system, SDR transceiver, and dual-polarization antenna, the RFSonde enables high-resolution IQ measurements across the S and X bands. Project outcomes include one journal article and four conference presentations.

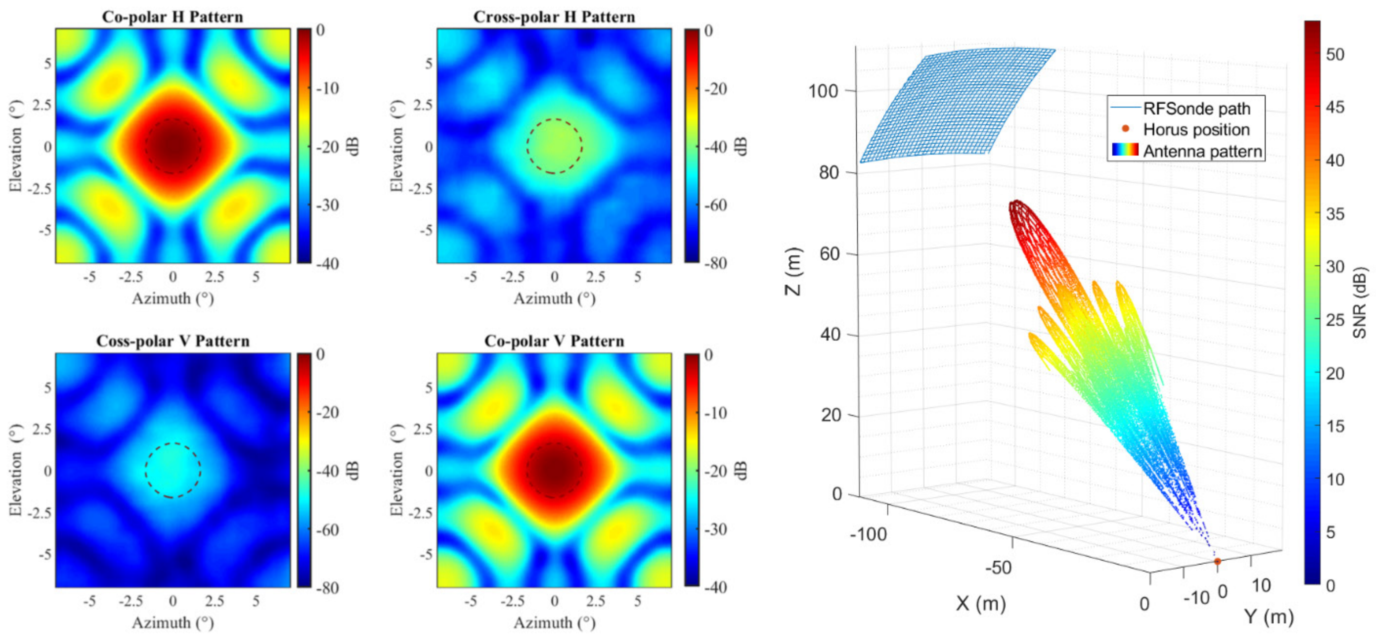


Figure 2-52: Example Horus antenna patterns measured with the RFSonde UAS system. The small figures to the left show the Co-Pol and Cross-Pol power measurements of the H and V polarizations. The large figure to the right shows a 3D visualization of the main beam of Horus which was reconstructed using power data collected with the RFSonde across the flight path in blue lines.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Stephen Gregg, Sebastián Torres
Project Title: Rotating PAR pathfinding using the ATD
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

This project explores the potential of a rotating phased array radar (RPAR) system as a cost-effective alternative to stationary four-faced PAR systems, aiming to achieve faster volumetric updates. The primary goal is to inform the NWS Radar Next Program by gaining valuable experience with key engineering aspects of RPAR operations, which will accelerate future research and development efforts. Using the Advanced Technology Demonstrator (ATD), which features a rotating antenna on an azimuthal turntable, the project focuses on developing and testing a new radar scheduler that supports RPAR operations, accounting for the complexities of combining mechanical and electronic beamsteering. The new radar scheduler is being used to evaluate different experimental concepts of operations (ConOps) that leverage PAR's unique capabilities (e.g., Schvartzman et al. 2021). Insights from this work will lay the foundation for future RPAR research and development. Accomplishments include designing and implementing radar control, scheduling, and scan monitoring software to enable the ATD to collect weather data while continuously rotating. Additionally, using an external tower as a reference, the pointing accuracy of the rotating ConOps was verified, confirming that the maximum azimuth difference between the external tower and the ATD's data does not exceed 0.1 degrees. Tangible outcomes include a new software capability that enables the ATD's ability to support RPAR operations.

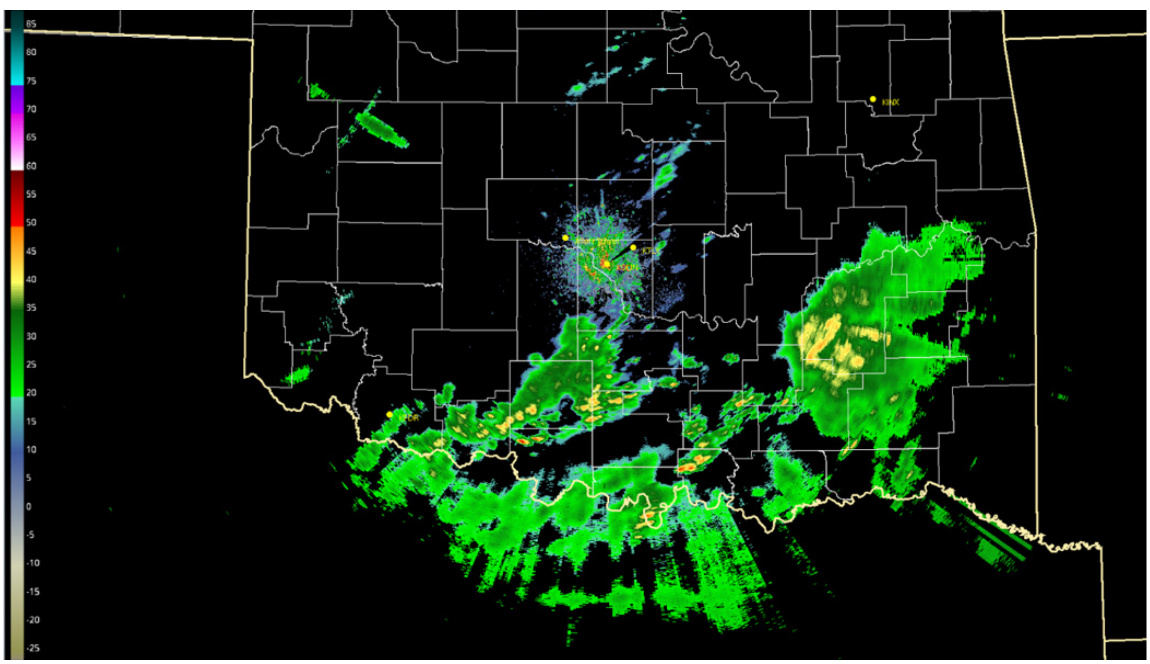


Figure 2-53: Real-time display of the reflectivity field of weather data collected by the ATD using a rotating ConOps on November 9, 2023.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Christopher Curtis, Robert Estes, Eddie Forren, Stephen Gregg, Igor Ivić, Rakshith Jagannath, Feng Nai, Sebastián Torres
Project Title: Demonstration of spoiled transmit beams on the ATD
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

This project focuses on implementing spoiled beams on the Advanced Technology Demonstrator (ATD) to speed up radar volume scans. A spoiled beam intentionally broadens the transmit beam, allowing multiple receive pencil beams to be digitally formed within the broadened main lobe. This technique can significantly accelerate scanning by a factor equal to the number of simultaneously formed receive beams. The first milestone involved engineering evaluations to verify the performance of the new software and calibration processes for spoiled beam modes. Once validated, scanning strategies were developed to use this mode for rapid-update radar data collection, supporting important meteorological research goals. Implementing spoiled transmit beams required substantial upgrades to radar subsystems, including modifications to real-time data processing infrastructure, the implementation of Remote Direct Memory Access (RDMA) technology and server upgrades to handle the increased data throughput. The Digital Beamformer was also updated to support various spatial sampling strategies, and new calibration processes were developed for the new radar beams. This project aims to demonstrate how spoiled beams can reduce scan time while assessing the trade-offs, such as reduced sensitivity and degraded angular resolution, compared to traditional pencil beams (Boettcher et al. 2022). Accomplishments include the implementation of spoiled beam operation on the ATD, which collected weather data to demonstrate time savings and trade-offs in data quality. Software was developed to support spoiled beam operation with various sampling options and handle the increased data rate. Additionally, a new calibration procedure was developed to produce correction factors for reflectivity and polarimetric variables. Tangible outcomes include 1 journal paper, 4 conference presentations, 1 NSSL technical report, and 1 new software capability.

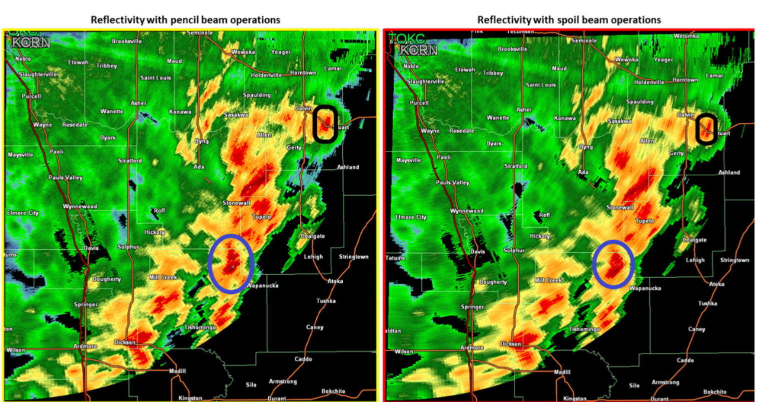


Figure 2-54: Comparison of reflectivity from pencil beam (left panel) and spoiled beam operations (right panel). While the general reflectivity patterns are similar, the reflectivity from spoiled beam operation has a smaller footprint due to its lower sensitivity. The increased beamwidth and sidelobe levels also caused degraded spatial resolution that appear as a smoothing of the data in azimuth (e.g., area circled in blue and black).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Noah Boeckman, Christopher Curtis, Robert Estes, Stephen Gregg, Sebastián Torres
Project Title: Demonstration of adaptive scanning on the ATD
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

This project focuses on developing adaptive scanning techniques for PAR systems to improve weather data collection. Adaptive scanning involves automatically adjusting radar-scanning parameters, such as beam patterns and scan strategies, based on the observed phenomena and mission needs. For example, adaptive scanning can enable faster updates in targeted regions, like severe storms, while reducing scans in clear air, thereby optimizing data quality and spatial sampling. The goal is to implement adaptive scanning techniques suitable for both stationary and rotating PAR systems. A key challenge is developing the necessary software infrastructure, including radar scheduling and user interfaces, to support real-time adaptive scanning. The project recently implemented a framework for adaptive scanning on the Advanced Technology Demonstrator (ATD), enabling the reimplementation of an adaptive focusing algorithm. The ATD is now being used to test this algorithm in real-time. Expected outcomes include a better understanding of how PAR's scanning flexibility can be applied in adaptive scanning frameworks and the demonstration of advanced scheduling techniques with multiple regions of interest. This project also sets the stage for future developments in adaptive scanning, potentially incorporating artificial intelligence and machine learning for cognitive scanning. By leveraging PAR's flexibility, adaptive scanning can optimize radar performance and ensure more effective data collection where and when it is most needed. Accomplishments include upgrading the ATD's user interfaces, radar scheduler, signal processor, and data recorders to support adaptive scanning algorithms, implementing and testing the adaptive focusing algorithm, and developing a radar emulation framework for performance testing. Tangible outcomes include 1 new software capability to enable adaptive scanning on the ATD.

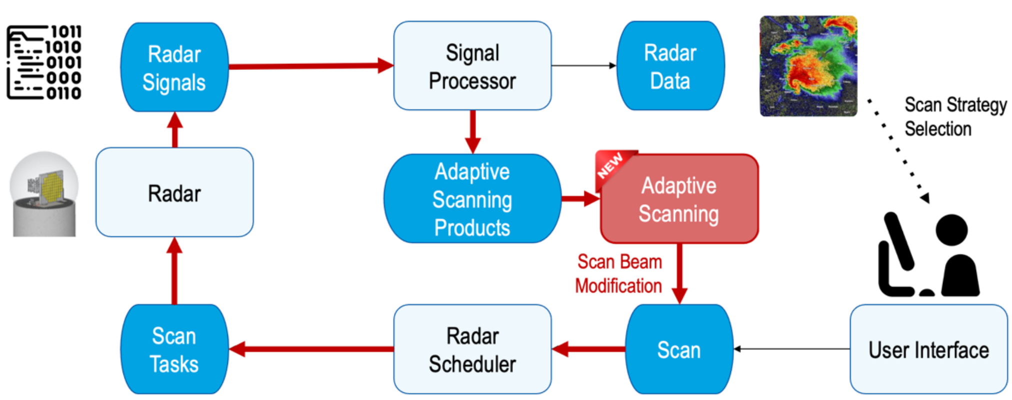


Figure 2-55: High-level block diagram of the scan-control function of the ATD. The closed-loop infrastructure for adaptive scanning is represented by the red arrows. This infrastructure allows for automatic, real-time scan modifications in response to radar observations and user needs.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Christopher Curtis, Sebastián Torres
Project Title: Pulse compression on PAR
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

This project explores the use of pulse compression in active phased array radars to enhance radar sensitivity without sacrificing range resolution. Pulse compression is particularly beneficial for solid-state transmitters, which have lower peak power compared to traditional tube-type transmitters. The primary focus of the project is to improve pulse compression performance by addressing system distortions that can degrade the performance of pulse compression and introduce undesired artifacts in the radar data. An optimization framework was developed to account for these distortions, aiming to enhance the performance of pulse compression on the Advanced Technology Demonstrator (ATD). The project is evaluating various methods for mitigating system distortions and assessing their impact on radar performance. Expected outcomes include identifying practical challenges and solutions for implementing pulse compression in weather radars, particularly for phased array systems. The ultimate goal is to refine the pulse compression technique so it can be applied to operational weather radar systems, improving the overall radar data quality. Accomplishments include implementing a new optimization approach for the design of pulse compression waveforms that accounts for system distortions, and developing a method to measure pulse compression performance using an external tower, including experimentation to identify the best tower candidates for testing.

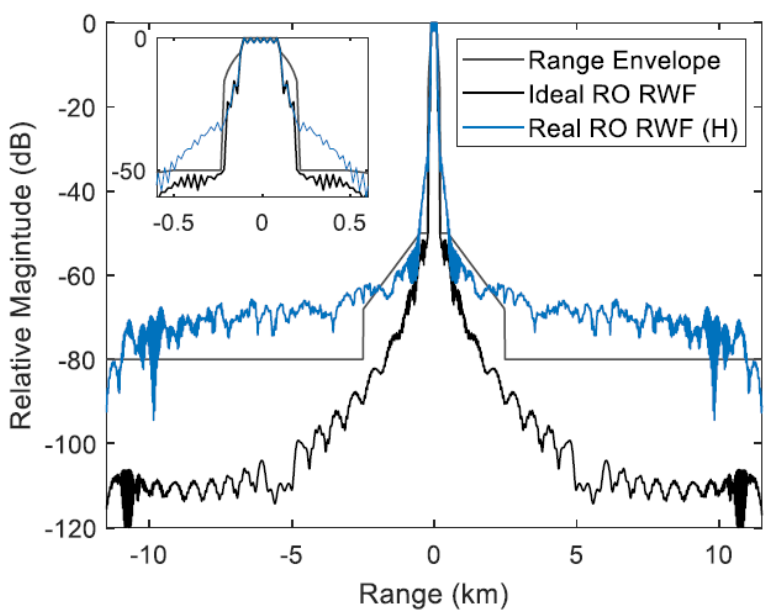


Figure 2-56: The black range weighting function illustrates the theoretical low range sidelobe performance of the optimized pulse compression waveform with respect to a desired range envelope; the blue range weighting function illustrates the actual performance of the pulse compression waveform after system distortion.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Christopher Curtis, Stephen Gregg, Sebastián Torres
Project Title: Non-conventional scanning strategies with PAR
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

This project investigates the use of advanced radar scanning strategies to enhance the collection of meteorologically relevant data with phased-array radars (PAR). PAR's unique capabilities, such as flexible beamforming and beamsteering, allow for non-conventional scanning techniques tailored to specific weather conditions. One such technique is the Range Height Indicator (RHI) mode, which provides detailed representations of vertically oriented phenomena like microbursts, especially when combined with dense vertical sampling (Pearson et al. 2023). However, using different scanning modes, such as Plan Positioning Indicator (PPI) and RHI, involves tradeoffs in spatial resolution and temporal updates. The project aims to identify the optimal combination of these modes to maximize radar data collection effectiveness. It also focuses on implementing advanced radar scheduling and user interface systems to support these non-traditional scanning strategies, referred to as "ConOps." This includes upgrading radar software to enable the collection of weather data using different ConOps. As a result, the project provides valuable insights into how various sampling modes influence radar data quality on PAR systems. Accomplishments include the development of software for the ATD, which provides a general framework for creating, executing, monitoring, displaying, and recording non-conventional scanning strategies. Four non-conventional scanning strategy modes were designed and implemented, including split-sector PPI, RHI, PPI with interlaced sparsely spaced RHIs, and PPI with interlaced dense RHI sectors. Tangible outcomes include new software capability that supports 4 new data-collection modes with the ATD.

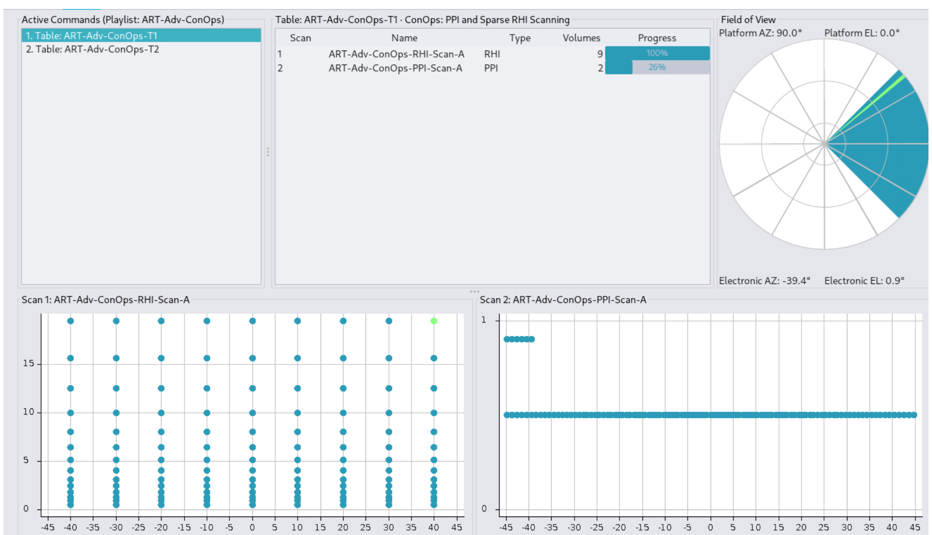


Figure 2-57: User interface for monitoring the progress of advanced scanning strategies in real-time, including high-level scanning strategy indicator (top row, first panel), scanning progress indicator (top row, second panel), mechanical and electronic steering indicator (top row, third panel), and low-level spatial coverage indicators (bottom row, first and second panels).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Christopher Curtis, Robert Estes, Stephen Gregg, Sebastián Torres
Project Title: Non-conventional transmission modes with PAR
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

This project aims to enhance the capabilities of active phased array radars (PAR) by exploring alternative transmission modes for meteorological data collection. PARs can quickly switch between different modes, enabling non-conventional scanning strategies that maximize the meteorological information obtained. The current default transmission mode for dual-polarization weather radars on the NEXRAD network is simultaneous horizontal and vertical (SHV) transmission, which provides three dual-polarization variables: correlation coefficient, differential reflectivity, and differential phase. However, additional information can be captured using modes such as linear depolarization ratio (LDR) and circular depolarization ratio (CDR). These variables offer valuable insights into hydrometeors and can be estimated through non-conventional transmission modes. This project investigates the benefits of LDR and CDR, as suggested in existing literature, and explores how these modes could be integrated into adaptive scanning strategies for real-time use, providing meteorologists with new tools for data analysis. The project also explores how different transmission modes can be utilized to develop unconventional scanning strategies that optimize the meteorological relevance of data collected by PAR systems. Accomplishments include the development of software to enable the use of LDR mode in weather scanning strategies on the ATD, which includes a real-time LDR display, upgrades to the signal processor, and updates to the data recorders for archiving LDR data. Additionally, hardware and software changes needed for CDR mode were investigated. Tangible outcomes include one new software capability that enables the collection of LDR data with the ATD.

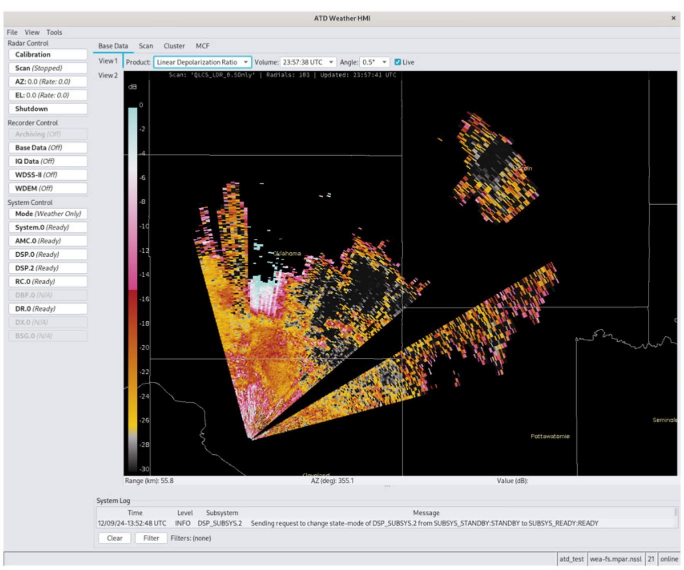


Figure 2-58: ATD real-time display of the LDR field from a hailstorm in Oklahoma City on 9/24/2024.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Christopher Curtis, Feng Nai, Sebastián Torres
Project Title: Adaptive beamforming on PAR
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

This project focuses on developing an adaptive beamforming algorithm for polarimetric phased array radars (PAR) to enhance data quality by reducing sidelobe contamination when using spoiled transmit beams. Adaptive beamforming dynamically adjusts the antenna pattern based on environmental conditions, improving signal reception and mitigating interference. This technique is particularly beneficial when using spoiled transmit beams, which elevate sidelobe levels and can introduce significant biases, especially in areas with strong reflectivity gradients. The algorithm works by using spatial covariance between receivers to minimize sidelobe contamination while ensuring that the antenna patterns remain calibratable. Traditional adaptive beamforming methods are unsuitable for weather radars because they can produce patterns that are difficult to calibrate. The goal of this project is to develop a new beamforming algorithm with constraints that maintain calibration while effectively mitigating sidelobe biases. This is the first adaptive beamforming method specifically designed for weather PAR, which allows the radar to produce more accurate and high-quality data in complex environments. Key accomplishments include the development of a constrained beamforming technique that adapts antenna patterns to reduce sidelobe contamination while ensuring accurate calibration. Additionally, a moving clutter filter was developed using space-time adaptive processing, and its effectiveness was demonstrated with data from the Horus radar (Kim et al. 2024). Tangible outcomes include 1 journal paper, 5 conference presentations, and the supervision of 1 Graduate Research Assistant (GRA).

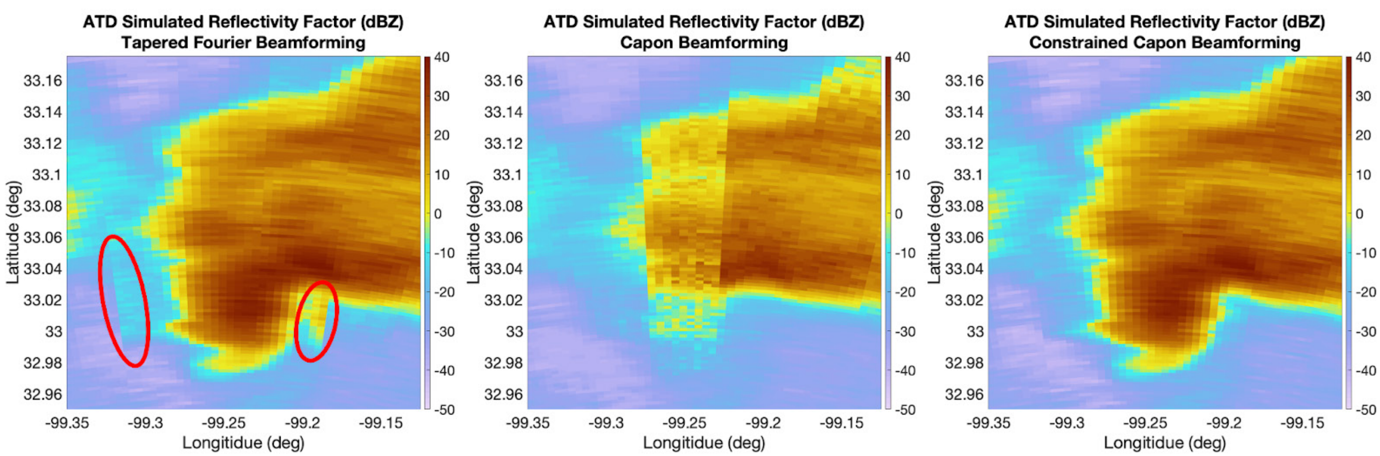


Figure 2-59: Calibrated reflectivity factor for conventional beamforming (left panel), conventional adaptive beamforming (middle panel), and constrained adaptive beamforming (right panel). Conventional beamforming produces calibrated beams but has significant sidelobe contamination in the circled regions. Conventional adaptive beamforming has a sector that is not well-calibrated, creating an undesirable artifact. Constrained adaptive beamforming is both well-calibrated and sufficiently mitigates the sidelobe contamination seen in conventional beamforming.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Kristofer Tuftedal, Terry Schuur, Jami Boettcher, Emily Blumenauer
Project Title: ATD and KOUN data collection
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program, improving observation quality and stewardship, and developing next-generation observational capabilities.

Weather data collection with the Advanced Technology Demonstrator (ATD) has been ongoing since 2022; hitting its stride in 2023 allowing for extensive collections in 2024. Over this period, we have collected over 300 hours of data. We have begun utilizing novel scan strategies too time/wear-and-tear intensive or not possible with conventional radars. These strategies include automated adaptive scanning, the interlaced collection of multiple Range Height Indicator (RHI) scans in-between each Plan Position Indicator (PPI) volume, and switching between the standard Simultaneous Transmit, Simultaneous Receive for “traditional” polarimetric variables (i.e., differential reflectivity, cross-polar-correlation coefficient) and an Alternating Transmit, Simultaneous Receive to collect non-standard polarimetric variables (i.e., linear depolarization ratio, co-cross-polar correlation coefficient; Ryzhkov et al. 2002). We have collected and continue to evaluate spoiled beam (i.e., wider in one axis than the other) data of various severe weather events to determine how spoiling affects data quality. We have also collected the first “raster” PPI data (i.e., scanning like an RHI with beams at specific PPI elevation angles) in order to better analyze the vertical temporal evolution of rotational intensity in convective storms. The KOUN WSR-88D was operated for most cases ATD was also collecting to allow for comparisons between the two systems. This effort has supported one UGRA as part of the OU REU program and has resulted in 14 conference presentations.

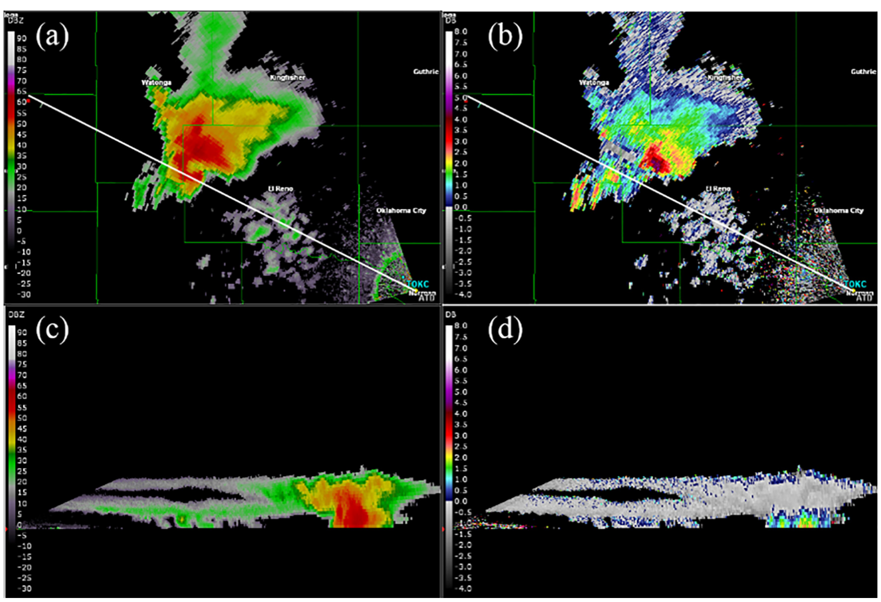


Figure 2-60: PPI plots (top) and RHI plots (bottom) from ATD of a tornadic supercell collected on 27 April 2024 at 21:26:06 and 21:26:04 UTC, respectively, for radar reflectivity (a, c) and differential reflectivity (b, d). The solid white line in (a, b) denote the location where RHI data are being collected, shown in (c, d).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributor: Emily Blumenauer
Project Title: Quantitative precipitation estimation with the ATD
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds

Currently, the National Oceanic and Atmospheric Administration (NOAA) is considering replacement options for its next generation of weather radars. One option is PAR, which employs electronic scanning and therefore has a faster volumetric update time (~1 minute) than the current Weather Surveillance Radar–1988 Dopplers (WSR-88Ds). The Advanced Technology Demonstrator (ATD), operated by NSSL, is an example of a research PAR that is being used to evaluate the feasibility of dual-polarization PAR technology. For this project, PAR quantitative precipitation estimation (QPE) is of particular interest. Questions have been raised regarding the impact an upgrade to PARs would have on QPE accuracy. Presumably, the improved temporal and vertical resolution of the PARs will lead to more accurate radar-based QPE. However, polarimetric PARs require more complex calibration compared to parabolic dish radars, and their measurement accuracy is not as robustly quantified compared to parabolic dish radars. To test the hypothesis that PARs can improve QPE accuracy, the ATD and KOUN, a WSR-88D also operated by the NSSL and collocated with the ATD, are used. Preliminary results show the ATD produces statistically better results than KOUN, where the most improvement is seen with hail and convective precipitation types. Because this project supports 1 GRA, expected outcomes from this project include at least 2 journal articles and 4 conference presentations. External partners involved in this project include NOAA/NSSL.

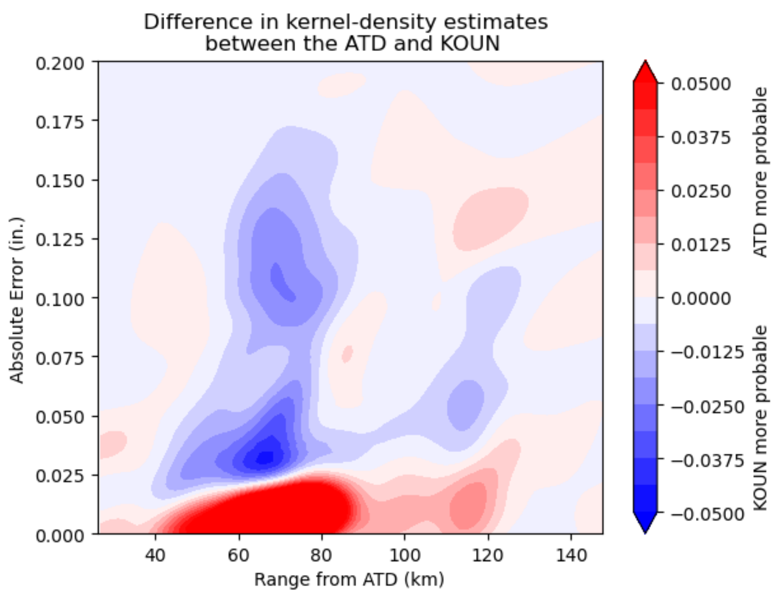


Figure 2-61: Difference in kernel-density estimates between the ATD and KOUN. The ATD has a higher density of lower error and KOUN has a higher density of higher error. These densities are consistent across all ranges.

CIWRO Themes: Weather Radar and Observations, Forecast Applications Improvements
CIWRO Contributors: Pierre Kirstetter, Shruti Upadhyaya
Project Title: Probabilistic precipitation rate estimates from ground-radar for hydrology
Relevance to NOAA: This project supports the NOAA mission by developing next-generation observational capabilities, developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, developing reliable probabilistic guidance products.

In this project a new decision-support capability for the Multi-Radar/Multi-Sensor System (MRMS), the Probabilistic quantitative precipitation estimation, is created with ground-based radars. Hydrometeorological applications require more than just one deterministic precipitation "best estimate" to adequately cope with the intermittent, highly skewed distribution that characterizes precipitation. This product is a gridded, CONUS-wide analysis of precipitation rates estimates that has the MRMS 2-min cadence and 0.01° resolution. The product includes both precipitation rates, uncertainties, and probabilities of exceeding thresholds for risk analysis. It is intended for nowcasting, post-event verification, and seasonal precipitation accumulations (Kirstetter et al., 2015). PQPE has been tested in the MRMS Research Testbed and in the Hydrometeorology Testbed (HMT) MRMS Hydro Experiment 2019 by NWS forecasters and NSSL scientists. Implementation in the MRMS research system (vMRMS) is completed and the code runs in real-time. Tangible outcomes from this project include 3 formal journal articles, 13 conference presentations, and 1 algorithm considered for transition at National Centers for Environmental Prediction (NCEP) Central Operations (NCO). External partners involved in this project include NOAA/NESDIS, NCAR, NWS, and NASA.

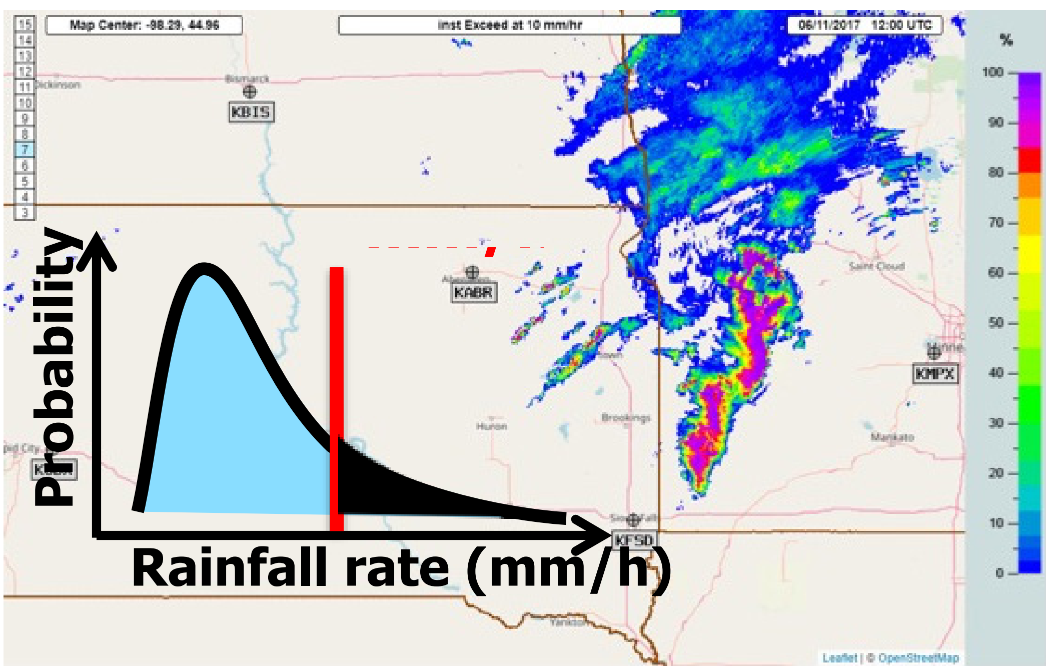


Figure 2-62: Probabilistic Quantitative Precipitation Estimation probability of exceeding 10 mm.h-1; on June 11, 2017 at 1200 UTC.

CIWRO Themes: Weather Radar and Observations
CIWRO Contributors: Robert Palmer, David Schvartzman, David Bodine, Boonleng Cheong, Caleb Fulton, Pierre Kirstetter, Jorge Salazar, Anthony Segales, Mark Yeary, Tian Yu, Guifu Zhang, Yoon Kim, Khuda Burdi, Ayano Ueki, Jonah Pehl, Laura Shedd, Brandon Cohen, Aimee Matland, Brianna Witherell, Junho Ho
Project Title: Development and demonstration of the Horus digital PAR
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the RadarNext program and by developing next-generation observational capabilities

The Advanced Radar Research Center (ARRC) has developed Horus, the first fully digital phased array weather radar, as part of ongoing efforts to explore next-generation weather radar technologies. PAR has been a major research focus of the ARRC for many years, culminating in the development of Horus, an S-band engineering demonstrator mounted on a truck for ease of deployment and transportability. The system is digital at every element and polarization and has been designed to be scalable and easily maintained. Since its inception, Horus has undergone multiple local deployments, leading to unique data collection and the first system-overview publication (Palmer et al. 2023). Research efforts span both engineering topics, including STAP, data/array efficiency, UAS-based calibration, and AI/ML adaptive sensing, as well as scientific studies focused on precipitation/microphysics, hail, and severe storms. Graduate students have played a key role, contributing to numerous journal publications. Notable studies include the first tornado observations (Cohen et al. 2025), advanced beamforming studies (Kim et al. 2024), and signal processing improvements (Schvartzman et al. 2024, Ueki et al. 2025). System improvements are ongoing, including software upgrades focused on ease of use and hardware modifications to enhance safety and accessibility for maintenance. Additionally, calibration studies are being conducted to assess the long-term stability of the mutual-coupling calibration method.

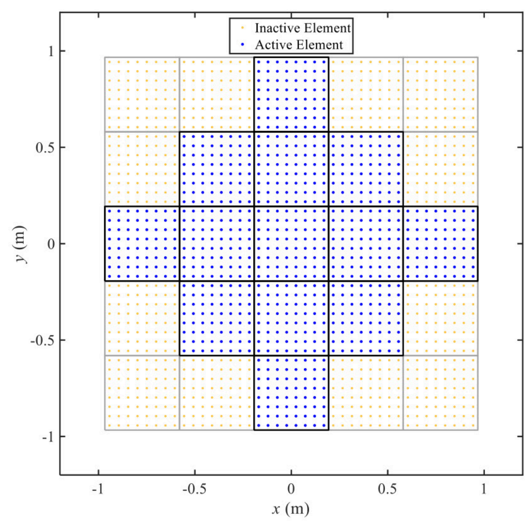


Photo 2-3: Photograph of Horus (with RaXPol) during a deployment on 8 August 2023. The right figure shows the current 13 active panels, which corresponds to 832 dual-pol elements.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Jeff Brogden, Karen Cooper, Gabriela Fisher, Carrie Langston, Timothy Miller, Mike Taylor, Robert Toomey
Project Title: MRMS Software Development
Relevance to NOAA: This project supports the NOAA mission by developing next-generation observational capabilities, improving observation quality and/or stewardship, enhancing capabilities for the Radar Next program and/or WSR-88Ds

The focus of this project is defined by the scientific research of all the teams creating Warning Decision Support System (WDSS)-II, Hydro Suite or MRMS based algorithms. We provide guidance, education, tools and expertise in real-time algorithm development and the integration of data into the MRMS system. We host a monthly collaboration meeting where teams can come to find out what is happening in the MRMS world, and about other research, etc. To advance the ability for scientists to work on any radar data set that operates at any elevation angle, we have created a new infrastructure called Integration of Dynamic Radar Elevation Scans (IDRES). IDRES is currently running in real-time on several Amazon Web Services (AWS) MRMS domains. Outcomes of this project include supporting major software suites, such as WDSS-II, Hydro Suite, Transportation, and FLASH.

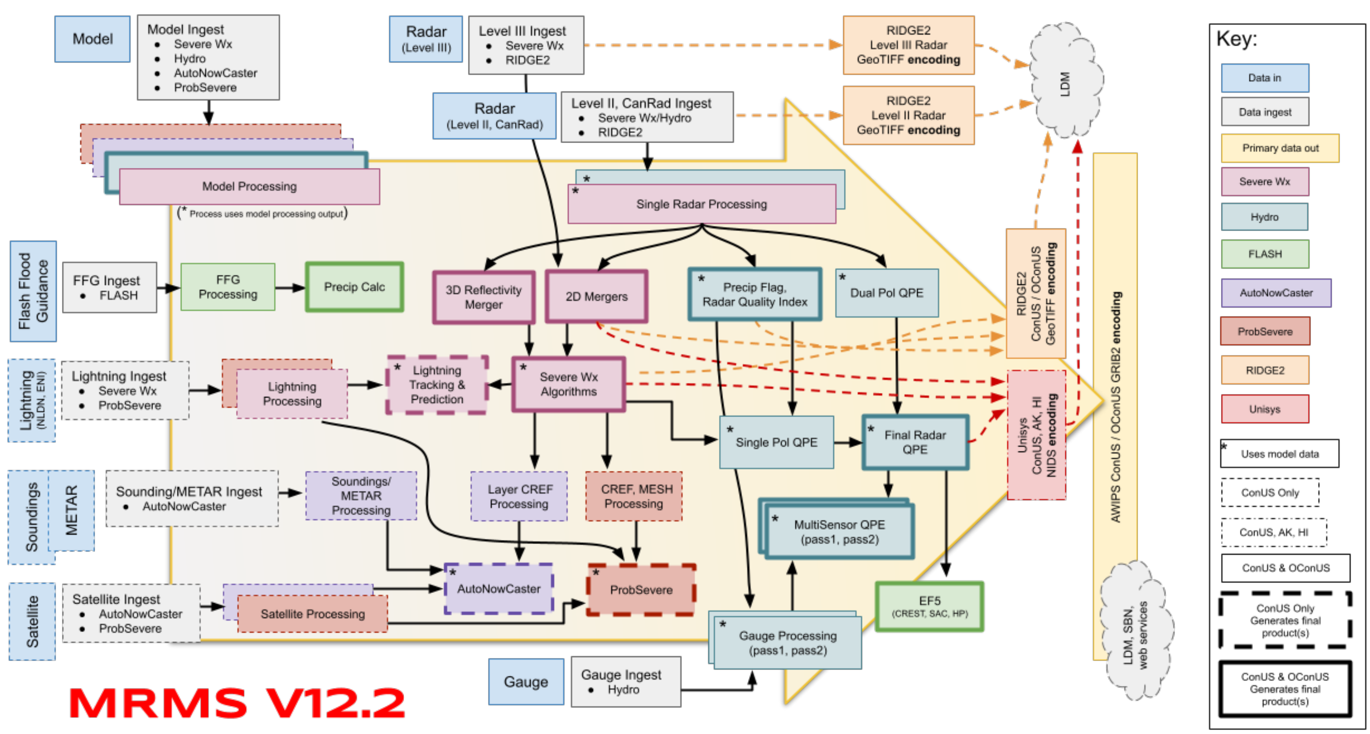


Figure 2-63: Overview of the workflow/dataflow for the MRMS system showing a high-level view of the various software processing suites as well as the flow of data through the system.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Ami Arthur, Jeff Brogden, Karen Cooper, Gabriela Fisher, Nathaniel Indik, Brent Kraninger, Carrie Langston, Timothy Miller, Mike Taylor, Robert Toomey
Project Title: MRMS Research to Operations
Relevance to NOAA: Improving observation quality and/or stewardship, Developing next-generation observational capabilities

CIWRO is responsible for keeping MRMS, NSSL's premier research-to-operations success story, running operationally. We are also pushing to develop faster transitions by moving MRMS development and operations to the commercial cloud. We support research-to-operations of MRMS technologies for the following entities: IDP@NCO (2 operation systems, and one QA system) – the main NWS operational system, Salt River Project, Taiwan, AWS (Dev for NCO and replacement for vMRMS, as well as a Climavision domain, KMA, Houston, NETile), and vMRMS. CIWRO has supported large scale research of algorithms by creating specialized domains: SETile for VORTEX/PERiLS, NETile for Transportation, Climavision CRADA, AF/KMA domain, and Houston domain.

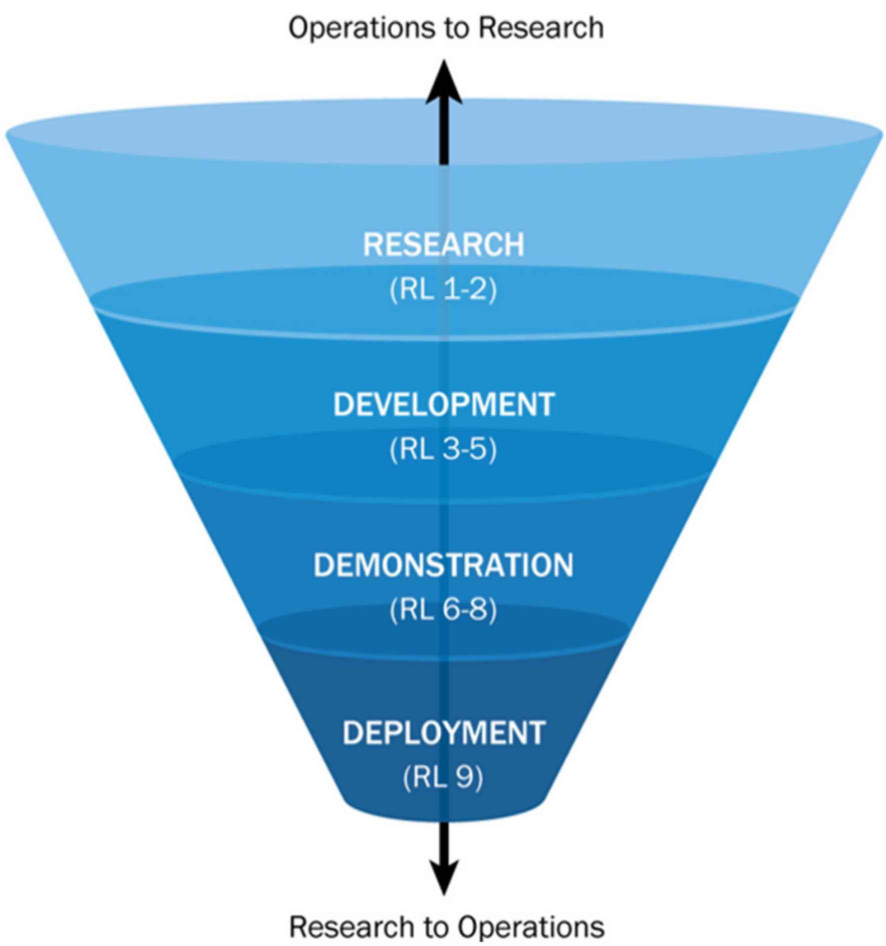


Figure 2-64: Research To Operations funnel for MRMS

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Ami Arthur, Jeff Brogden, Karen Cooper, Nathaniel Indik, Brent Kraninger, Carrie Langston, Mike Taylor, Robert Toomey
Project Title: Web tools and Geospatial data sets and analysis
Relevance to NOAA: Improving observation quality and/or stewardship; developing next-generation observational capabilities; creating/improving a trusted analysis of record for model verification/nowcasting

CIWRO has supported over 40 web tools for data visualization and verification, serving both operational and research needs. These tools include the Operational Product Viewer, Internal Research Product Viewer, Gauge vs. QPE Comparison, Custom QPE Accumulations, a suite of ROC research tools, the EMS Research Viewer, and an eMPE proof of concept. To enhance accessibility and deployment efficiency, the team has created containerized versions of these tools, allowing for quick integration into new environments such as AWS, SRP, and custom domains. Beyond web tools, we have provided critical GIS data and analysis, supporting a wide range of meteorological and environmental applications. Our work has included generating wind turbine interference tables for all CONUS, OCONUS, and Canadian radars, developing terrain files for NEXRAD, Canadian S-Band, KMA, and Climavision radars, and conducting hybrid scan/height analyses for various radar locations. Additionally, the team has curated low-water crossing location datasets and performed distance analyses that have incorporated demographic and economic spatial data to support congressional briefings on proposed gap-filling radar locations. Through these efforts, we have enhanced the accessibility, accuracy, and impact of weather and environmental data.

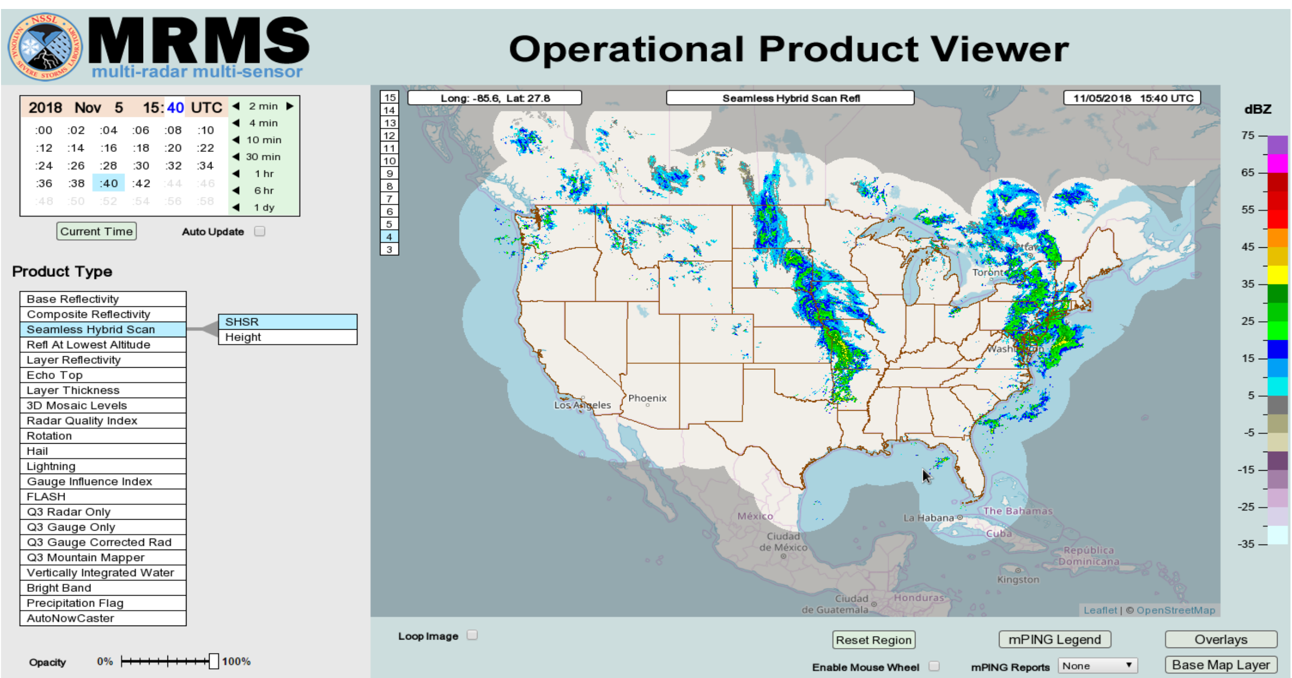


Figure 2-65: Example of the Operational Product Viewer, the main web tool CIWRO supports

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Karen Cooper, Carrie Langston, Mike Taylor
Project Title: Dataflow into and out of NSSL/CIWRO
Relevance to NOAA: Improving observation quality and/or stewardship; Developing next-generation observational capabilities; Creating/improving a trusted analysis of record for model verification/nowcasting

CIWRO has managed a vast amount of data flowing into and out of the lab, supporting not only MRMS but a wide range of other users. These data feeds have included radar datasets such as NEXRAD Level 2 and Level 3, Canadian S-Band Radar Data, Climavision, KMA, and gap-filling radars, as well as model data from RAP, HRRR, GFS/RTMA, RRFS, and others. Additionally, we have handled gauge data from multiple networks, satellite data, the Canadian Precipitation Analysis System, and numerous other sources. The data has been utilized by a diverse set of users across NSSL and beyond, including HWT, WoFS, NASA, regional and national forecast centers, the National Water Center, CIMSS, SPC, NCO, WCOSS, WPC, NCAR, GSD, the Hurricane Center, GSL/ESRL, and the Aviation Weather Center. It has also contributed to critical modeling efforts such as RAP, HRRR, and the National Water Model, as well as FLASH outputs. Furthermore, ACME has supported external partners through various working agreements and has provided data to many other entities, ensuring broad accessibility and impact across the meteorological community.

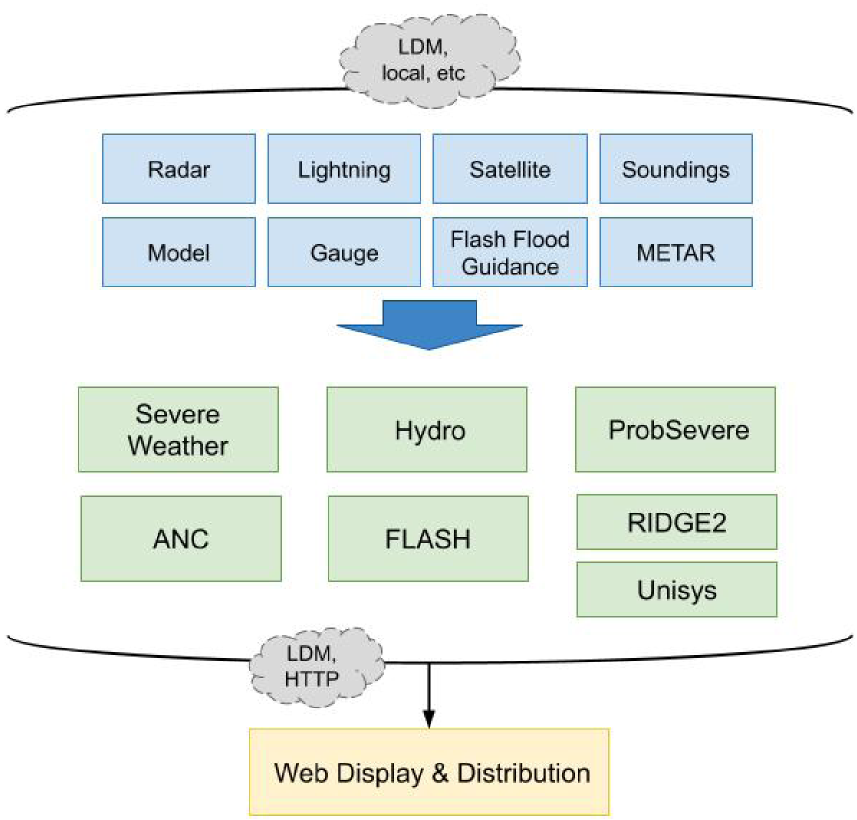


Figure 2-66: MRMS uses my types of data as input and produces output for a variety of systems

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributor: Jeff Brogden
Project Title: mPING winter weather impacts
Relevance to NOAA: Incorporating social-science principles in new technology/training; Developing reliable probabilistic guidance products

CIWRO collaborated with the Weather Prediction Center (WPC) to add a “Winter Weather Impact” category, along with 10 new descriptions or report types. WPC has used these additions for verification and to improve research on the Winter Storm Severity Index and ProbWSSI. Since November 2022, nearly 18,000 “Winter Weather Impact” reports have been submitted, contributing valuable data to ongoing research. Additionally, there has been potential for a new section of mPING dedicated to reporting general weather-related impacts, with scientists in our Behavioral Insights Unit expressing strong interest in this expansion.

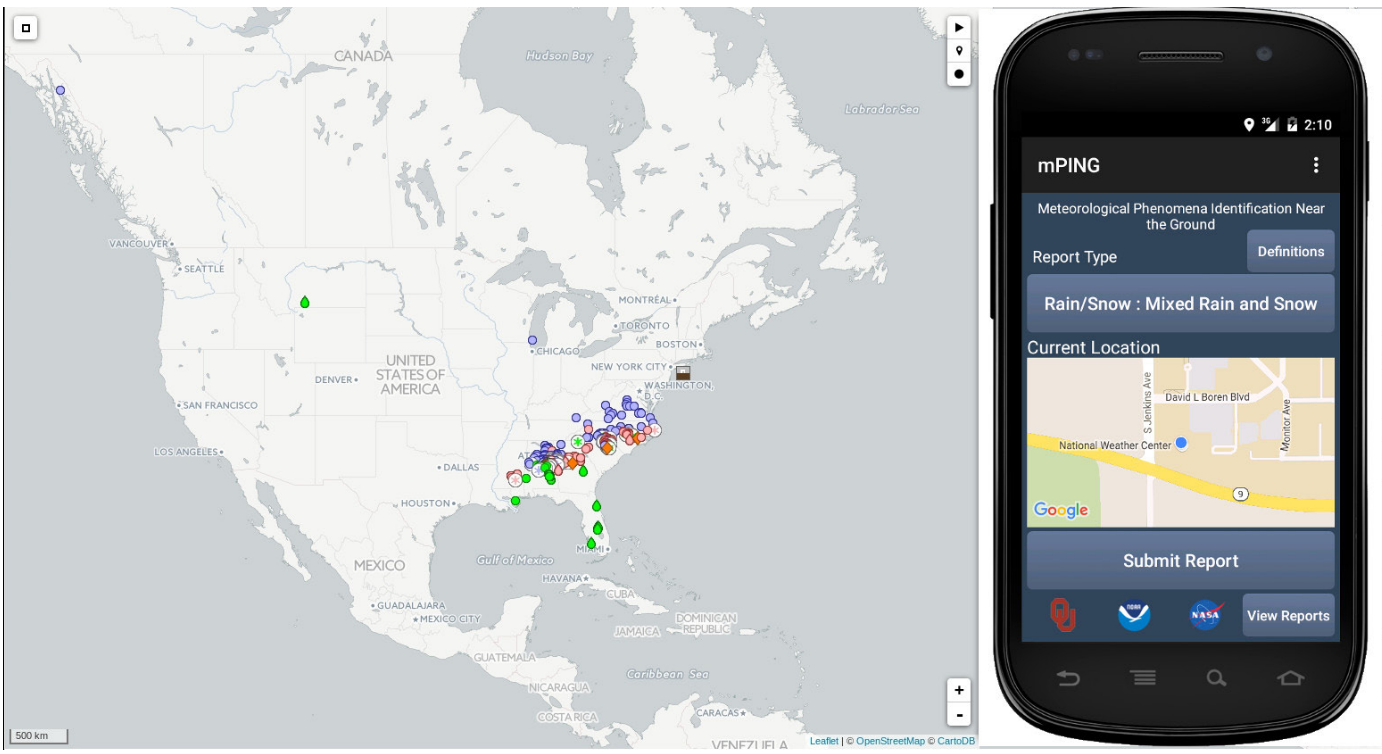


Figure 2-67: The mPING app (left) and display of reports during a severe winter storm (right)

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributor: Lin Tang
Project Title: Removing wind farm and terrain contamination from radar reflectivity
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and enhancing capabilities for the Radar Next program and/or WSR-88Ds.

The project documents areas where wind farm turbines or challenging terrain are contaminating reflectivity (Z) fields. Fields of cross-correlation data are used to distinguish between meteorological and non-meteorological radar returns. Corrections to Z are made via the use of neighboring pixels to the contaminated data (if the contaminated area is small) or using median Z for acceptable data within more widespread contamination. The quality-controlled Z data is available at a two-minute time interval and 1-km^2 spatial resolution. Case study analyses have shown the technique consistently removes turbine and terrain contamination from the Z data fields. This ultimately removes the negative impacts that Z contamination has on quantitative precipitation estimates (QPE) and acts to improve radar and QPE data for forecasters using the Multi Radar Multi-Sensor (MRMS) system. Tangible outcomes from this project include two technology transfers to operations in April (updated US turbine tables) and August (implemented Canadian tables) 2022, two Radar Operations Center (ROC) Technical Interchange Presentations, and a ROC final report.

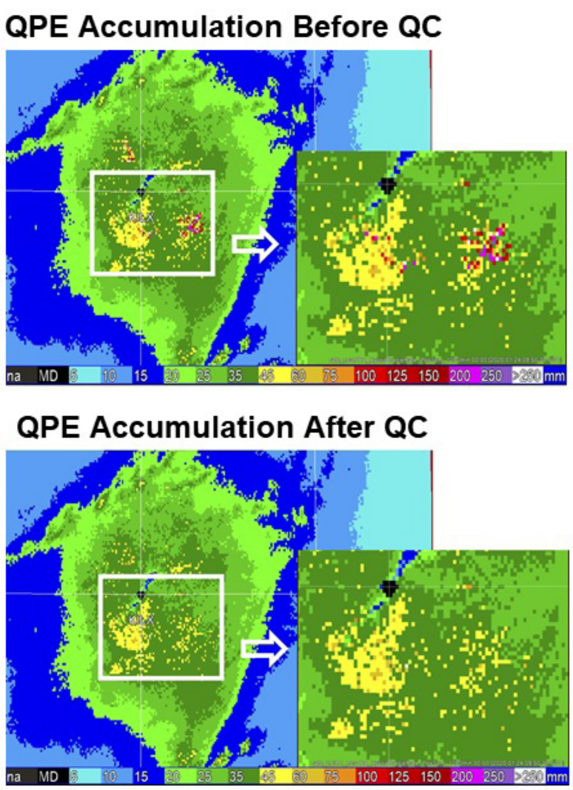


Figure 2-68: 24-h QPE accumulations before (top) and after (bottom) radar quality control was applied to reflectivity fields to remove wind turbine induced contamination.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Jeff Brogden, Valery Melnikov
Project title: Improving quality control of MRMS products from non-meteorological radar data artifacts
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and improving observation quality and/or stewardship.

The MRMS system presents radar images from multiple WSR-88D radars. An example is presented below. It was long noticed that MRMS output may be questionable. In the image below, one can see wide areas of negative Z_{DR} from KPDT. This was widespread rain and it is not possible that raindrops can produce negative Z_{DR}. The question is what causes negative Z_{DR} bias? Is this a malfunction of the transmitter or the receiver? The goal of the project was to link biased products with radar malfunction radar parameters. This was an attempt to develop a new methodology to assess whether "performance" data from radars correlates to quality control (QC) issues seen within MRMS products. Our research identified 13 out of 317 "performance" data fields, 0 out of 296 alarm codes, and 9 out of 23 "performance" data change rates as potential QC metrics. Conclusions of analysis given for inclusion in the final report: Limited impact of the potential QC metrics since the applicable range encapsulates a small percentage of the overall radar dataset, is restricted to the beginning of the volume scan, and misses many instances of the same QC issue. The tangible outcome of this project includes 6 presentations to the WPO meetings and 2 meetings with the ROC engineering branch.

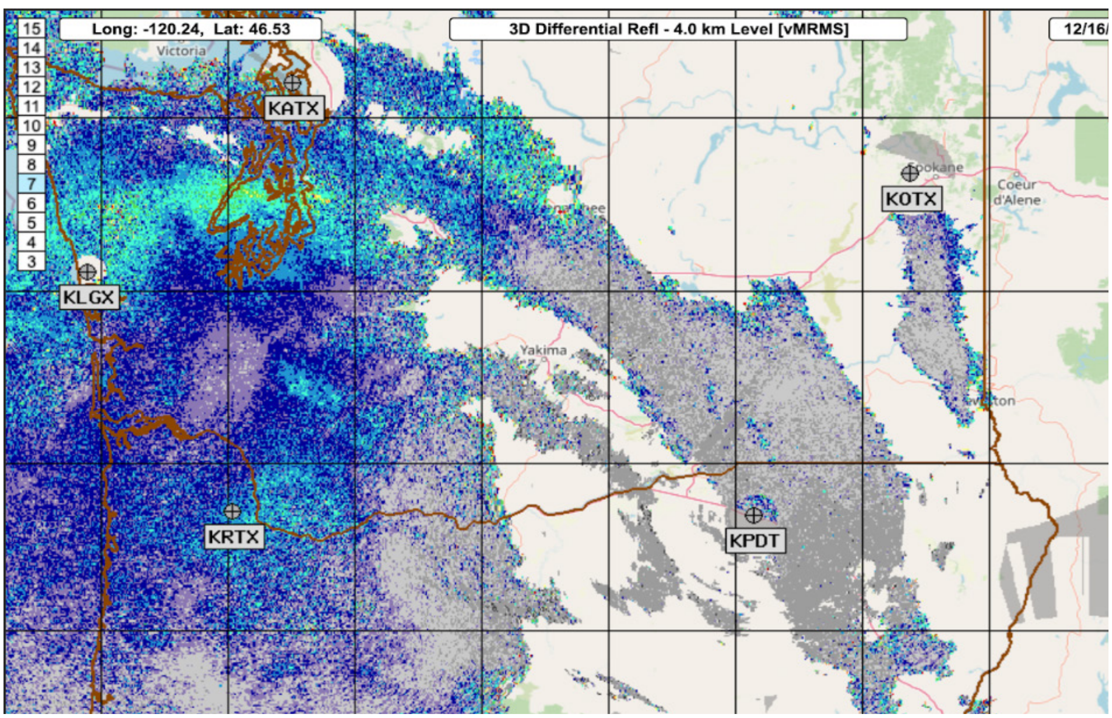
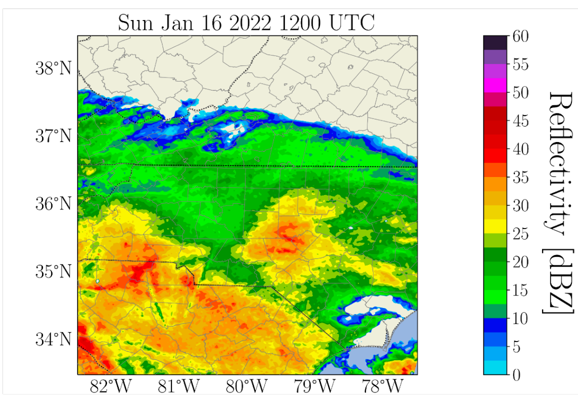


Figure 2-69: ZDR image from multiple sites shows negatively biased Z_{DR} values from KPDT.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Edwin Dunnavan, Heather Reeves
Project Title: Investigating the impact of riming fraction on the MRMS SBC precipitation types
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and by improving continuous engagement with partners.

This sensitivity study, conducted to aid the Federal Aviation Administration (FAA), investigated the impact of riming fraction on the Multi-Radar/Multi-Sensor (MRMS; Zhang et al. 2016) Spectral Bin Classifier (SBC; Reeves 2022) surface precipitation type output. Riming fraction in the SBC model is a tunable and uncertain parameter but it is currently set to be constant. Fifty-two sensitivity tests were conducted by varying the riming parameter from 1 (unrimed snowflakes) to 5 (graupel). Modifying the riming parameter from 1 to 5 changed freezing rain classifications to ice pellet classifications by 25% on average whereas these modifications changed rain classifications to snow classifications by 40% on average. This project also investigated the possibility of using the MRMS hydrometeor classification algorithm (HCA) as a way to dynamically change riming fraction. However, for twenty-one of the freezing rain and ice pellet cases that have MRMS HCA data available, the degree of association between HCA-detected graupel and ice pellet mPING crowd-sourced reports was only 0.115 and the odds ratio was just over unity (1.65). This project has resulted in 1 technical report for the FAA.



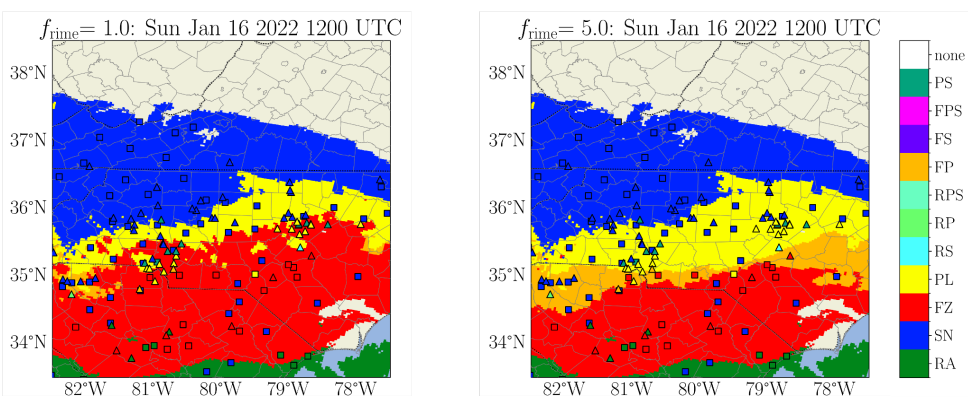


Figure 2-70: Comparison of Radar reflectivity at lowest altitude (RALA; top) with MRMS SBC output using a riming parameter of 1 (bottom left) and 5 (bottom right).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Adam Werkema, Heather Reeves
Project Title: Improved quality control for light winter precipitation
Relevance to NOAA: This project supports the NOAA mission by improving observation quality and/or stewardship

This project creates and evaluates a new radar quality control algorithm for the MRMS system. This algorithm improves upon the current quality control algorithm by retaining more instances of light winter precipitation (e.g. light snow and drizzle) on the MRMS display. The algorithm utilizes variations of dual-polarization signatures to discriminate between light winter precipitation and non-meteorological radar echo. This algorithm will provide a more accurate radar display of ongoing precipitation to forecasters and decision-makers who rely on weather radar. Statistical analysis of the new algorithm over six months shows that the probability of retaining precipitation on the MRMS display increased from 92.7% to 95.4%. Most notably, the probability of retaining drizzle increased from 27.3% to 55.8%. The probability of retaining non-meteorological echo only increased by 0.5%. Tangible outcomes from this project include 2 conference presentations. An external partner is the Federal Aviation Administration (FAA) Aviation Weather Research Program.

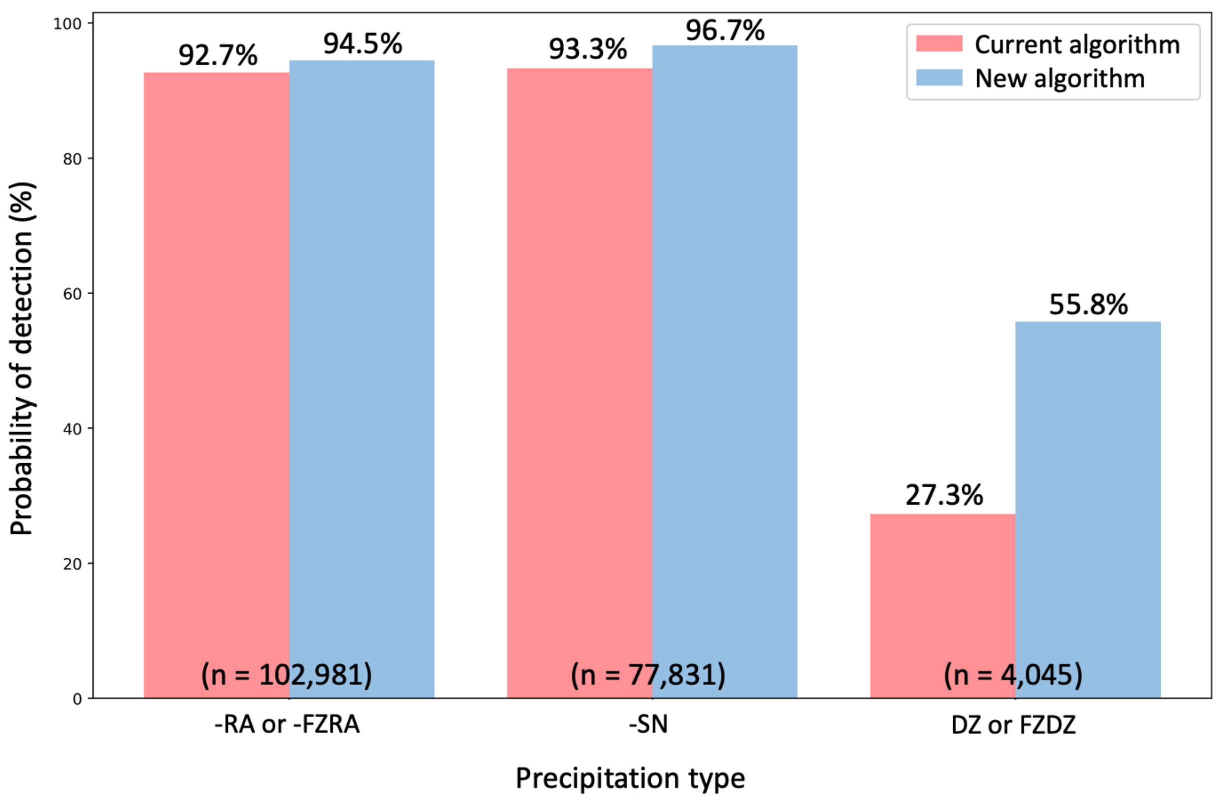


Figure 2-71: The probability of detection (retention) for both the current MRMS quality control algorithm and the new algorithm being developed in this project. Results are broken down into precipitation types: light rain or light freezing rain (-RA or -FZRA), light snow (-SN), and drizzle or freezing drizzle (DZ or FZDZ).

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Andrew Rosenow, Jilliann Dufort, Heather Reeves
Project Title: Creation and verification of gridded snow rate
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

Partners are requesting real-time information on snow rate - how quickly snow is falling - from NWS partners. The recent addition of Snow Squall Warning products also introduces short-term snow rate into the warning process. Despite this, there are no dedicated decision support analyses for snow rate. This project seeks to address those holes using the MRMS framework. To do this however, the role of Snow-to-Liquid Ratio (SLR) must be explored. SLR algorithms have limited research behind them, and there is almost no guidance on which SLR relationships to use in certain situations. Initial research has shown that the best SLR algorithm for ensemble predictions of snowfall vary in time, space, and based on ensemble member (Rosenow et al. 2023). These differences due solely to SLR choice can have real impacts on decisions made based on the analysis or guidance provided to partners. Tangible outcomes include one formal journal publication and five conference presentations. An external partner for this work is the University of Utah.

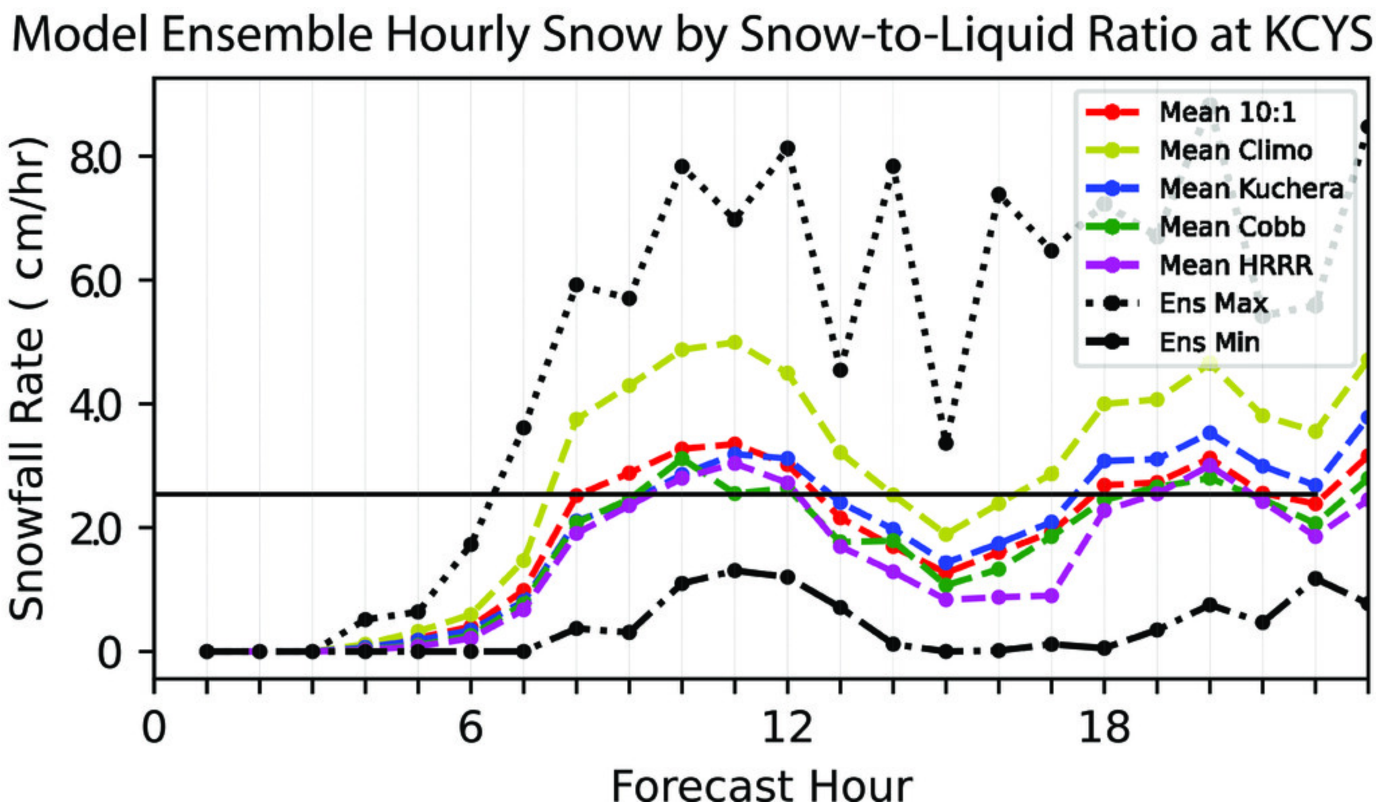


Figure 2-72: Hourly snowfall rate across the HRRRE ensemble and all SLRs for Cheyenne, WY, for the 13 Mar case. Colored lines represent ensemble mean snowfall rates for each snowfall forecast.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Stephen Cocks, Lin Tang
Project Title: Significantly improved MRMS operational QPE during high-impact events
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions.

This project continues to improve the Multi Radar Multi Sensor (MRMS) Dual Pol based quantitative precipitation estimates (QPE) accuracy for warm season precipitation events. The product is a gridded, CONUS-wide analysis of instantaneous rainfall rates and accumulations, primarily, at 1-h, 3-h, 6-h and 24-h cadences at a 1-km^2 spatial resolution. It is intended for use by forecasters during warning operations, as well as input for a variety of hydrological models (including the National Water Model) and numerical weather prediction models. Statistical analysis for data since 2021 has shown the current operational MRMS Dual Pol QPE has significantly reduced error and uncertainty as compared with quality-controlled gauges. New algorithm changes to improve MRMS Dual Pol QPE performance for a wider range of rain events have also been finalized as of July 2024 and are available to NWS forecasters as an experimental product. Tangible outcomes from this project include 1 technology transfer to operations (May 2022), 4 conference presentations, and 1 algorithm update ready for transition to NWS operations. External partners involved in this project include the NWS.

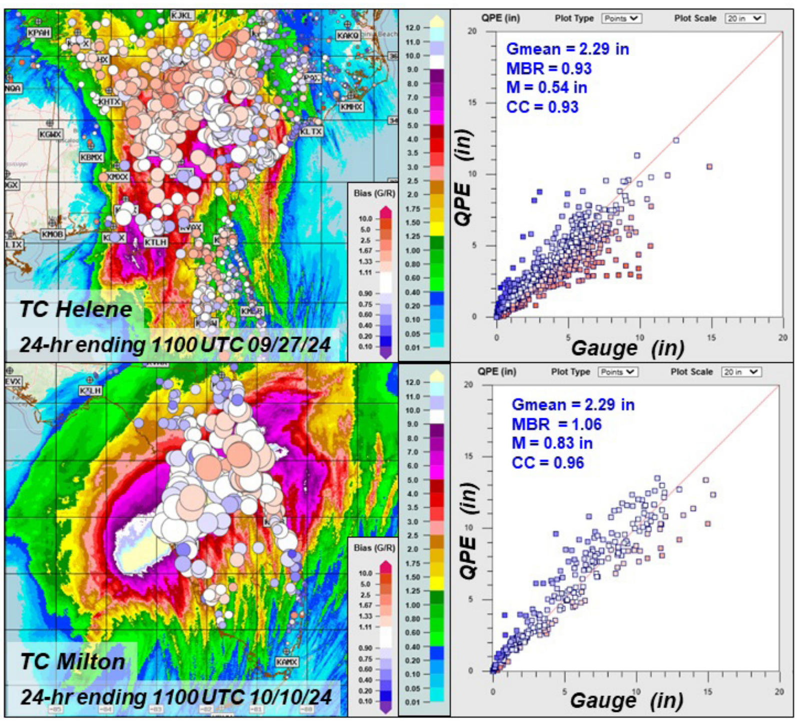


Figure 2-73: 24-h QPE accumulations, gauge bias bubbles and associated QPE vs Gauge scatter plots for period ending 1100 UTC 27 September and 10 October 2024. The first 24-h period was associated with rainfall from the remnants of Tropical Cyclone Helene over the Southern Appalachians. The second 24-h period was associated with Tropical Cyclone Milton as it tracked over central FL. 'Gmean' refers to mean gauge while 'MBR', 'MAE' and 'CC' refer to Mean Bias Ratio, Mean Absolute Error and Correlation Coefficient.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Andrew Osborne, Michael Simpson
Project Title: MRMS machine learning derived QPE for the Western US
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions.

This project was developed due to the inadequacies of radar only quantitative precipitation estimates (QPEs) in the Western US. The Western US low level radar coverage, required for the beam volume to sample precipitation close to the surface to generate accurate QPE, often has significant gaps due to the siting of radars in and amongst challenging terrain. A Machine Learning QPE algorithm was developed to determine whether this technique could provide significantly more accurate QPE than currently available operational radar only MRMS QPE. As illustrated below, testing has shown significant success with Western US precipitation events. Currently, the ML QPE algorithm is being tested and refined over other regional domains in the Western US. The medium-term plan is to have the ML QPE algorithm running in the MRMS real-time testbed by 2026. It is intended for use by forecasters during warning operations, as well as input for hydrological and numerical prediction models. Tangible outcomes from this project include a prototype ML QPE algorithm, one journal article and four conference presentations.

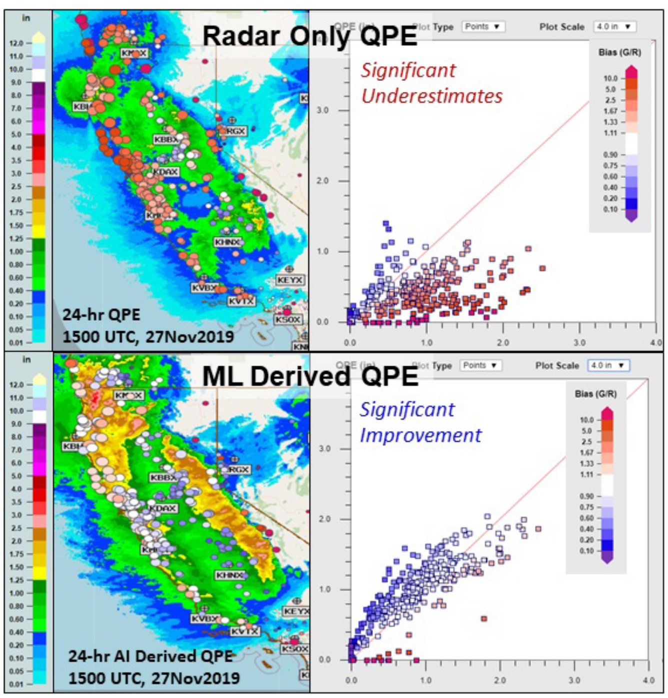


Figure 2-74: 24-h QPE accumulations, gauge bias bubbles and associated QPE vs Gauge scatter plots for MRMS Radar Only QPE (top) and Machine Learning Derived (bottom) QPE for the period ending 1500 UTC 27 November 2024. Precipitation is mainly confined to the Southern Oregon and California West Coast region. Radar only QPE has a distinct dry bias due to many of the radars being sited in and amongst challenging terrain resulting in the sample beam volume located significantly above the surface. The ML Learning QPE is utilizing a number of variables such as raw radar, terrain, and environmental model data and in this case has removed much of the dry bias.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributor: Nana Liu
Project Title: Development of a satellite QPE utilizing machine learning
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions.

This project started in the late summer of 2023 with the purpose of developing a machine learning (ML) based QPE utilizing GOES satellite data with the purpose of using it to fill in low level coverage gaps in radar coverage within the CONUS. The goal is to have high quality quantitative precipitation estimates (QPE) derived from several data sources available for use by forecasters throughout the CONUS. The ML model uses Multi Radar Multi Sensor (MRMS) precipitation rates and GOES16 IR brightness temperatures as input training data with the former data remapped to match the advanced baseline imager (ABI) grids. A post calibration technique has been developed to refine the ML model precipitation probability performance after model test runs. Initial work involved testing different architectures for the ML model to better understand model performance for different loss functions and different input variables. Currently, the ML model is being tested on its ability to create a precipitation/no precipitation mask based on the input data provided. The eventual goal is for the ML model to produce precipitation rates for comparison with the MRMS validation data. Tangible outcomes from this project include one conference presentation. The external partners in this project are NOAA NESDIS and OU ARCC.

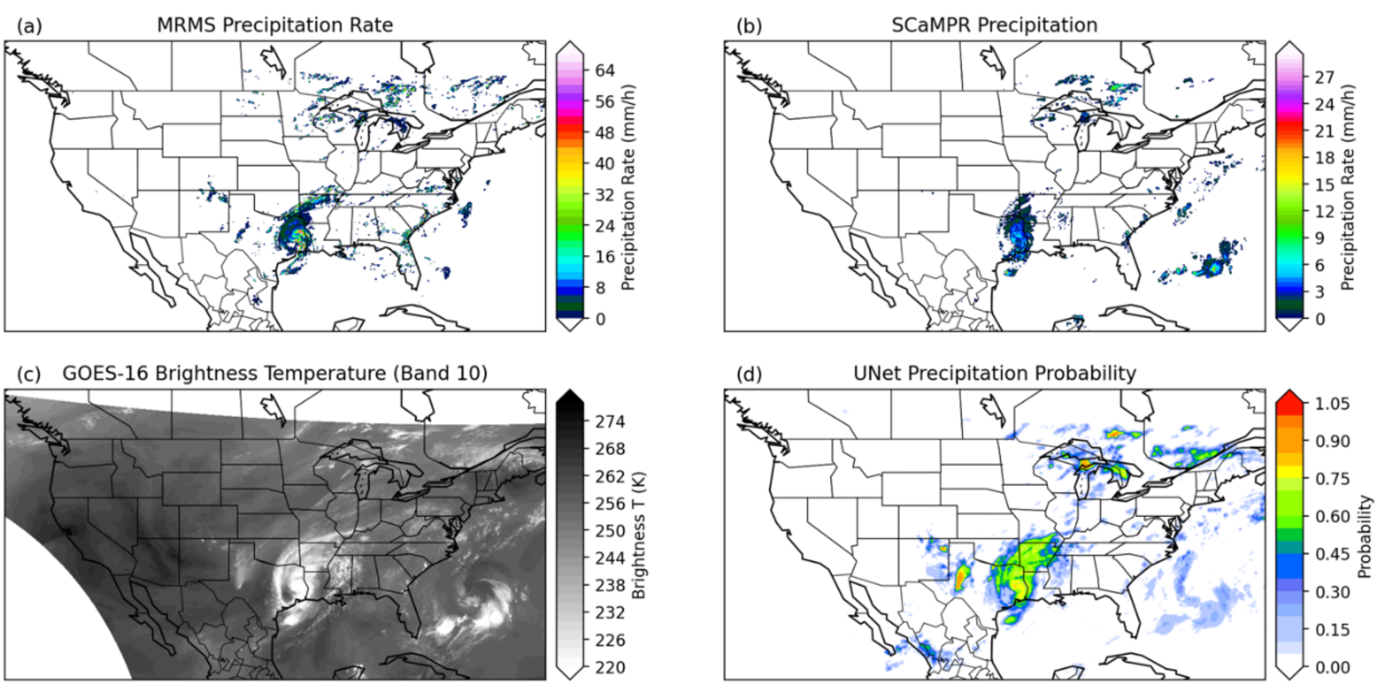
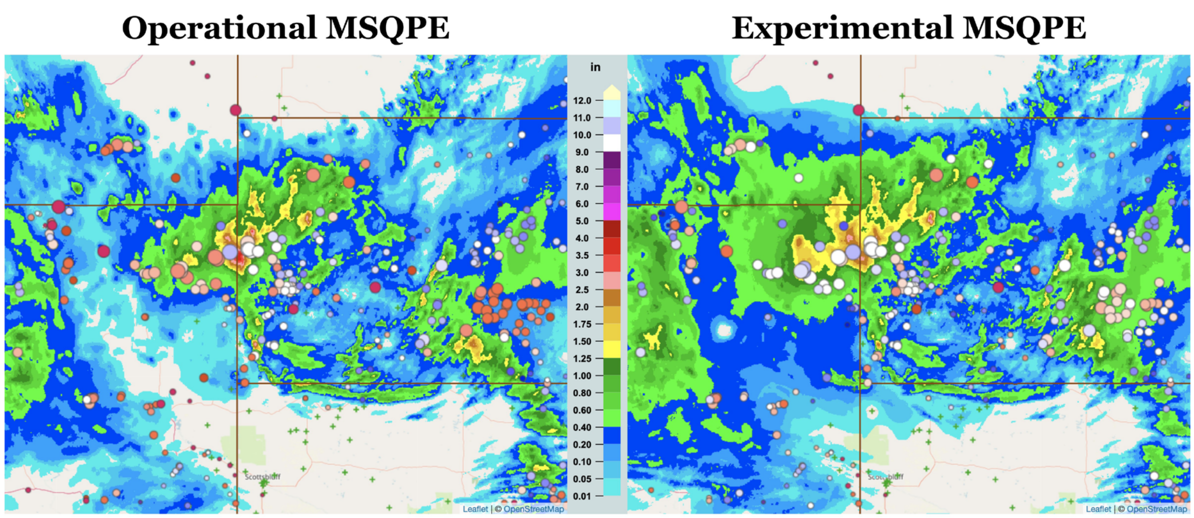


Figure 2-75: Case comparison on 1800 UTC 8 July 2024, (a) MRMS precipitation rate, (b) Self-calibrating Multivariate Precipitation Retrieval (SCaMPR) using IR and microwave-based rainfall estimates, (c) GOES-16 brightness temperature (Band 10), (d) ML predicted probability of precipitation occurrence.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributor: Steven Martinaitis
Project Title: Multi-Sensor QPE advancements
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions.

The Multi-Sensor QPE (MSQPE) product within MRMS has been operational in the NWS since 2020, yet there are still some challenges and limitations that need to be addressed within the product generation and its accuracy. This project advances the science and logic of the MSQPE scheme by addressing four different parts of the scheme: 1) the blending logic between the radar-derived QPE and the gap-filling sources, 2) how we define accurate radar coverage based on the MRMS Radar Quality Index (RQI) product, 3) gauge correct the model quantitative precipitation forecasts (QPFs), and 4) creating a new gauge ingest that would increase the number of surface observations used in the product creation. These efforts are designed to reduce known areas of underestimation (particularly in complex terrain), mitigate biases in model derived QPF, and allow for greater use of radar data in warm weather regimes. The updates to the RQI product and the gauge corrected model QPF have been running experimentally in realtime. The logic changes to the MSQPE scheme have gone through case evaluation and the ingest of new gauge observations have been tested locally (by case and by realtime) on a local machine. A more complete and accurate coverage of QPE benefits NOAA operations and applications such as forcing for the National Water Model. The current tangible outcomes from this project are 1 conference presentation and 2 algorithm updates ready for transition to NWS operations. External partners and collaborators include the NWS and SynopticData.



Bias Ratio (R/G): 0.799 RMSE (mm): 6.655 Correlation: 0.727

Bias Ratio (R/G): 1.065 RMSE (mm): 4.953 Correlation: 0.860

Figure 2-76: Example 24-hour MSQPE accumulation ending 1300 UTC 15 May 2024 for the operational (left) and experimental MSQPE logic with statistical evaluations. Bubble plots represent the the independent CoCoRaHS daily gauge data and its comparison to the gridded data, where reddish bubbles represent an underestimation of MSQPE, bluish bubbles represent an overestimation of MSQPE, and white bubbles represent equivalent good MSQPE values.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributor: Tyler Pardun
Project Title: A comparison between tornadic and non-tornadic QLCS mesovortices using a multi-radar analysis of operational and experimental MRMS products
Relevance to NOAA: This project supports the NOAA mission by furthering our understanding of QLCS mesovortices through the use of MRMS blended WSR-88D observations and aims to improve the predictability of tornadic QLCS mesovortices.

Quasi-linear convective system (QLCS) tornadoes have become a key research focus due to their rapid development, shorter lifespan, and shallower rotation compared to supercell tornadoes, making them difficult to forecast and warn. This study examines 121 tornadic and 153 non-tornadic (null) QLCS mesovortices across the CONUS using the MRMS system to identify differences in mesovortex evolution leading to tornadogenesis. The multi-radar framework enables a three-dimensional analysis of storm-scale characteristics near the surface and aloft. Tornadic mesovortices are nearly 1 km deeper and show stronger cyclonic rotation about 20 minutes before tornadogenesis. They also exhibit greater near-surface divergence through 6 km AGL and deeper convergence through 4 km AGL. Specific differential phase is typically higher in tornadic events, while differential reflectivity varies by region. Close-proximity mesovortices (≤75 km from radar) show higher variability than those farther away.

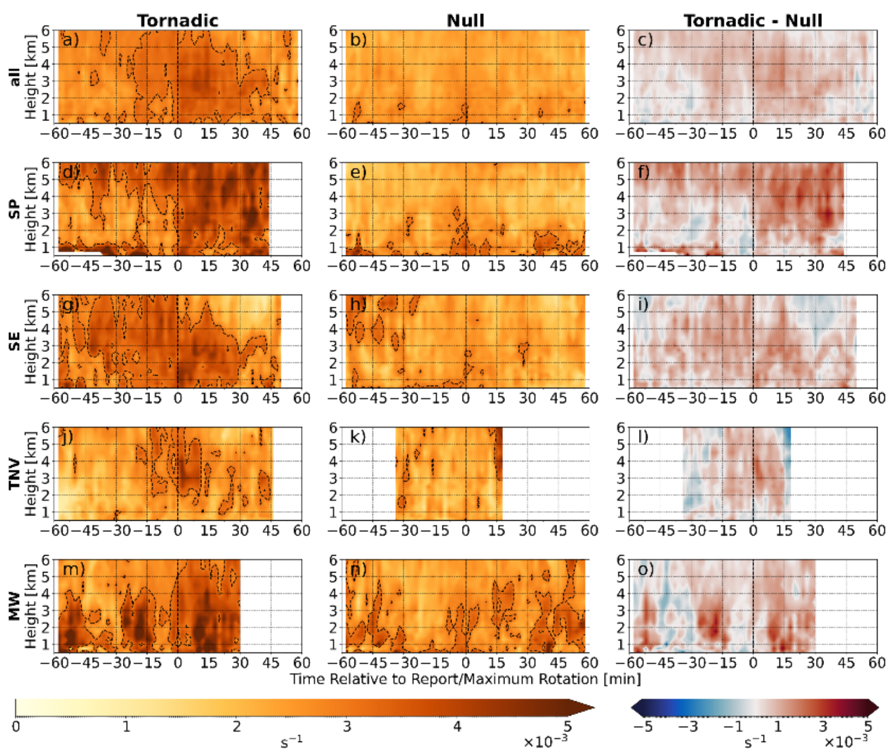


Figure 2-77: Median time-height cross sections of Divergent Shear for (left column) tornadic and (middle column) non-tornadic mesovortices with the difference between the median shown in the rightmost column for all regions, southern plains (SP), southeast (SE), Tennessee Valley (TV) and the Midwest (MW). Values are contoured at 0.003 .

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Steven Martinaitis, Dean Meyer, Stephen Cocks, Jackson Anthony
Project Title: Development of a mobile instrumentation platform
Relevance to NOAA: This project supports the NOAA mission by improving observation quality and/or stewardship and enhancing capabilities for the Radar Next program and/or WSR-88Ds.

This project was part of a collaboration with NSSL to design and develop a mobile instrumentation platform. The project called TOTAL (Telemetry of Observed Total Accumulated Liquid) has the goal of placing various, novel precipitation instrumentation in various environments and events (instead of waiting for weather to come to a specific location) to gather data on precipitation accumulations to further advance the science on radar QPE and improving the liquid equivalent values of winter precipitation. Another goal of the project is to improve gauge accumulations through wind underestimation studies that go beyond what is in the current literature. Instruments available for the TOTAL trailer include standard weighing gauge and tipping bucket gauge, disdrometer, forward scatter sensor, hotplate snow gauge, micro radar, and a mesonet rack to gather temperature, wind, pressure, etc. The trailer is designed to be self-sufficient with on-board computers and communication systems as well as the ability to run on battery power or direct power plug-in. The data planned to be gathered from the trailer can be analyzed through intercomparisons of surface observations as well as comparing with local radar and atmospheric data to gain new insight and relationships on how to improve precipitation estimates. The TOTAL trailer can be paired with WSR-88Ds as well as new radar technology (e.g., PAR) to help improve radar-derived precipitation estimates. The current tangible outcome from this project is the construction of the TOTAL mobile instrumentation platform.

Photo 2-4: Image of the new TOTAL mobile instrumentation platform during its first test deployment outside the National Weather Center on 1 November 2024. Instruments on the trailer during this test included the heated tipping bucket, weighing gauge, disdrometer, FD70 forward scatter sensor, CoCoRaHS gauge, and mobile mesonet rack.

CIWRO Themes: Weather Radar and Observations, Mesoscale and Stormscale Modeling
CIWRO Contributors: Michael Stock, Malachi Bowen, Joseph Berry, Christopher Schnieder Sarah Stough, Jacquelyn Ringhausen, Vicente Salinas, Vanna Chmielewski, Mackenzie Boylson, Matthew Miller
Project Title: Lightning mapping array measurements
Relevance to NOAA: This project supports the NOAA mission by creating/improving a trusted analysis of record for model verification/nowcasting, improving observation quality and/or stewardship, and improving continuous engagement with partners.

CIWRO supports an over 30-year history of NSSL lightning observations made by Lightning Mapping Array (LMA) technology through instrument support, data collection, and data archival efforts. LMAs facilitate detailed mapping of lightning flashes in three-dimensional space and time, producing integral information toward identification and diagnosis of lightning processes as well as connections between lightning and severe weather production. LMAs are typically fixed networks. However, in the past five years, the permanent installation of the network has been augmented by the development of mobile sensors toward a deployable LMA. The teams' continued support of mobile LMA deployments, measurements, and archival improve CIWRO and NSSL's capabilities to support worldwide research partnerships and collaborations. Tangible outcomes from this project include 3 peer-reviewed journal articles, 5 published datasets, and 26 conference presentations. External partners involved in these efforts include NMT/LMA Technologies. A number of partnerships have evolved from collaborative data provision and use.

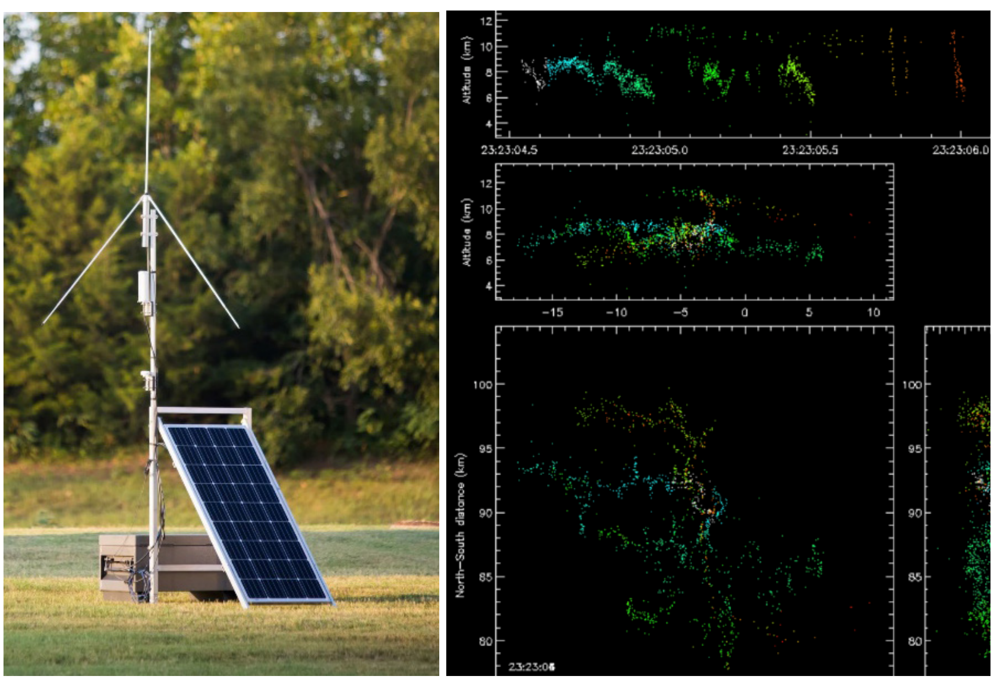


Figure 2-78: Photograph of a mobile LMA sensor (left) and Time-height, longitude-height, latitude-height, and planar maps of the very high frequency emissions of single lightning flash detected by the LMA (right).

CIWRO Themes: Weather Radar and Observations, Mesoscale and Stormscale Modeling
CIWRO Contributors: Vanna Chmielewski, Michael Stock, Jacquelyn Ringhausen, Vicente Salinas
Project Title: Propagation, Evolution, and Rotation in Linear Storms (PERiLS) field campaign
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions; enhancing capabilities for the Radar Next program and/or WSR-88Ds; and developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

PERiLS was a collaborative field campaign to sample and characterize near-storm environments and storm processes in tornadic quasi-linear convective systems and non-classical tornadic storms across the Southeast United States in the late winter and early spring seasons of 2022 and 2023. The team supported the campaign by collecting measurements of lightning in sampled storms and comparing them with data collected from other platforms and efforts in the coordinated campaign. Key results from the team's analyses include confirming that relationships between lightning and areas of rotation closely resemble those more commonly observed in supercell storms, lending insights into the processes by which QLCSs produce and support tornadic rotation. Tangible outcomes from this project include 1 peer-reviewed journal article, 2 published datasets, and 15 conference presentations. Key external partners involved in the lightning measurement project components include TTU, among others in the broader campaign.

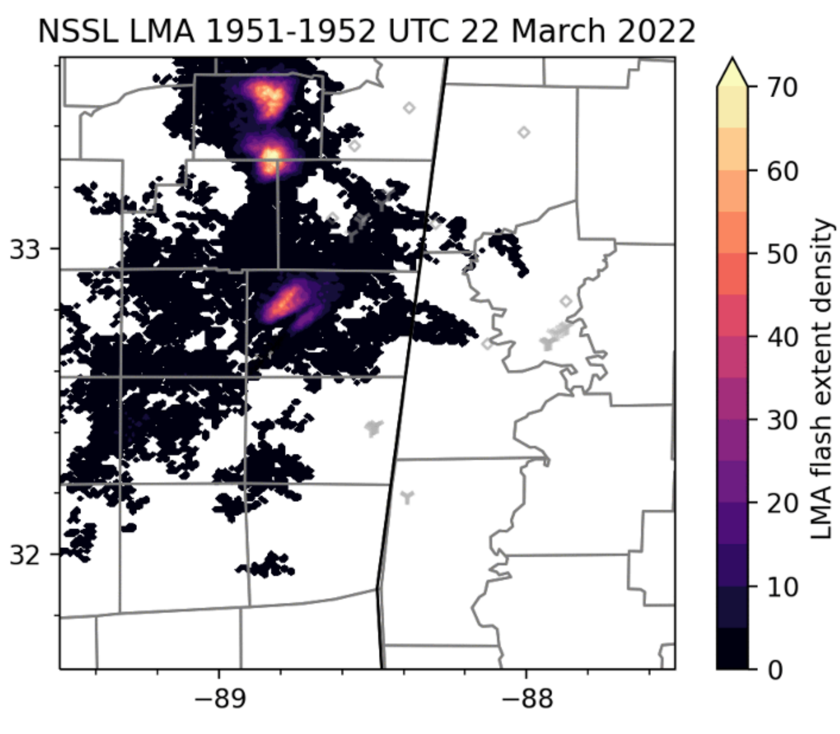


Figure 2-79: Lightning flash extent density (FED) obtained from mobile LMA observations during its deployment as part of the PERiLS field campaign. Areas with increased FED indicate more prolific lightning activity, most commonly associated with updraft invigoration and convective intensification.

CIWRO Themes: Weather Radar and Observations, Mesoscale and Stormscale Modeling
CIWRO Contributors: Michael Stock, Joseph Berry, Jacquelyn Ringhausen, Christopher Schnieder
Project Title: The Lake Effect Electrification (LEE) project
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions; creating/improving a trusted analysis of record for model verification/nowcasting; and developing next-generation observational capabilities.

The LEE project was a collaborative field campaign to sample and diagnose microphysics, electrification, and lightning processes in winter clouds and lake effect snow. The field campaign took place near Lake Ontario in the 2022-2023 winter season, where ISG team efforts included support of the mobile LMA and launches of electric field meters and particle imagers during the project as well as subsequent data archival and analyses. Key results from the team's analyses show that lake effect snow storms are electrified with a large lower positive charge region, and that lightning initiation is closely associated with wind turbine locations. The team is also preparing a follow-on project proposal. Tangible outcomes from this project include 1 peer-reviewed journal article with more in preparation, 2 published datasets, and 6 conference presentations. Key external partners involved in this project included SUNY Oswego, GTRI, and TTU, among others in the broader campaign.

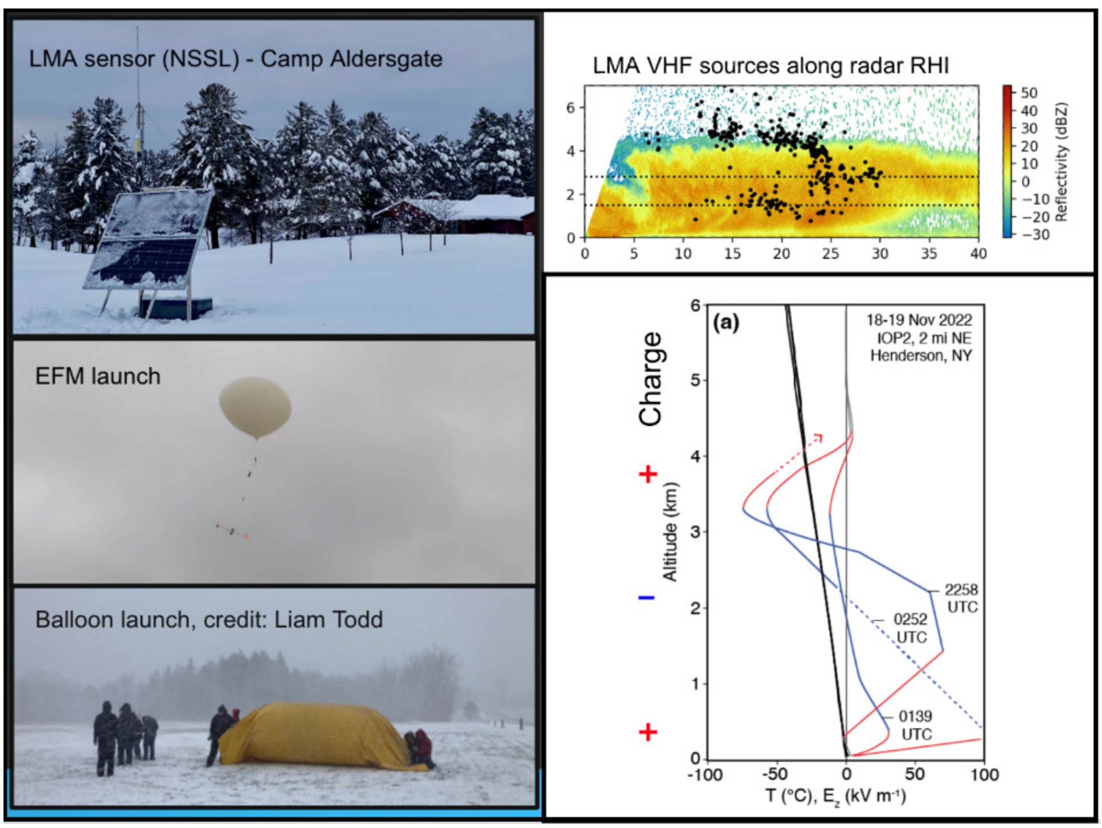


Figure 2-80: Photographs of LMA sensor, balloon with EFM payload, and launch activities (left images). LMA measurements overplotted on a vertical cross-section of radar reflectivity (color fill), showing lightning propagation along gradients in reflectivity indicative of microphysical transitions (top right). Changes in charge structure profiles inferred from consecutive EFM launches (bottom right).

CIWRO Themes: Weather Radar and Observations, Mesoscale and Stormscale Modeling
CIWRO Contributors: Michael Stock, Joseph Berry
Project Title: Improved lightning observations
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions; improving observation quality and/or stewardship; and developing next-generation observational capabilities.

Ongoing work to explore new lightning observing technologies for lightning location and interpretation (e.g., Long Wavelength Array, high-speed video data collection, slow-antenna field measurements, radar scattering of lightning channels), as well as provide ground validation for existing technologies to improve lightning detection and interpretation (e.g., video observations of lightning ground strike locations). Tangible outcomes from this project include 2 peer-reviewed journal articles, 1 published dataset, and several conference presentations. External partners involved in this project include UNM, SNL, TTU, UND, and the ARRC.

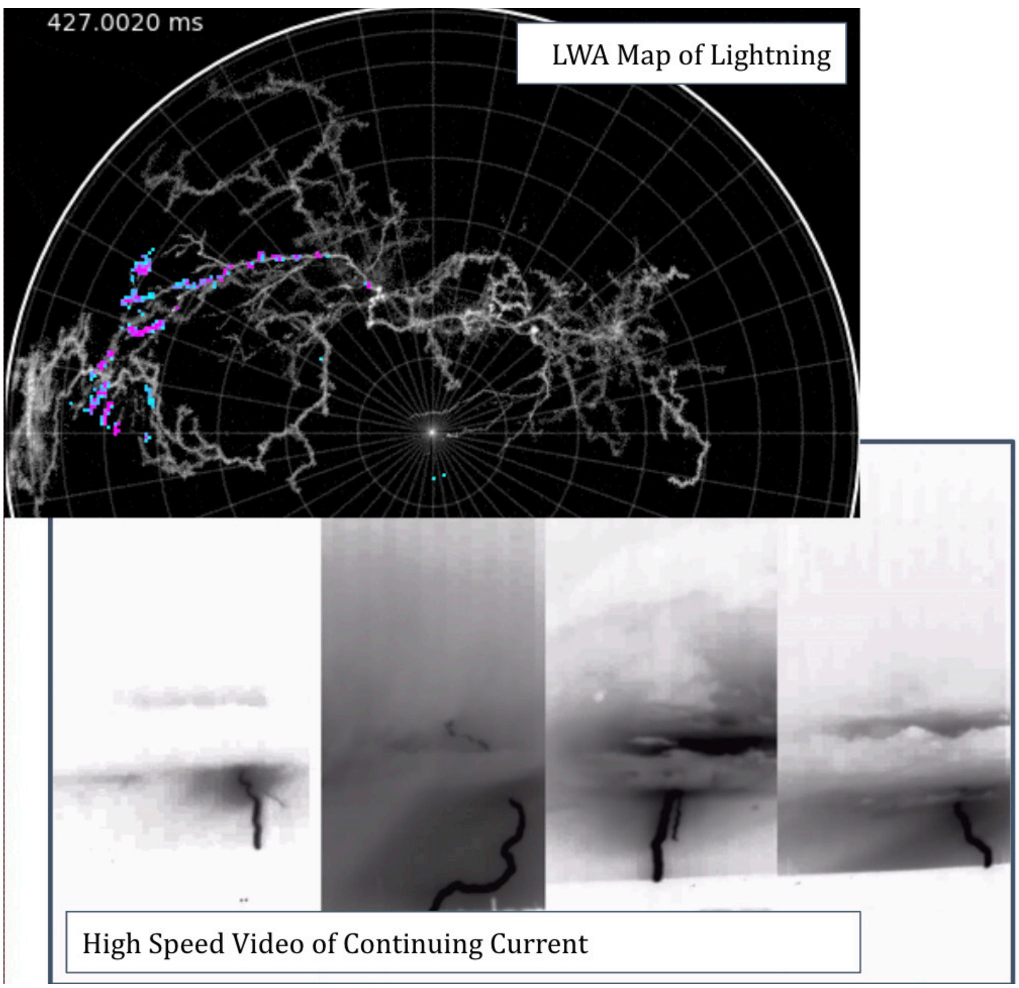


Figure 2-81: Detailed map of lightning propagation captured by the LWA (top). Capture from high speed video documenting development of continuing current (bottom).

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements, Sub-seasonal-to-Seasonal Prediction for Extreme Weather
CIWRO Contributors: Sarah Stough, Jacquelyn Ringhausen
Project Title: Unified lightning data
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds, improving observation quality and/or stewardship, and developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

Lightning data are available in operations from two ground-based networks as well as the GOES Geostationary Lightning Mappers (GLMs). The ground-based networks and the GLMs all observe and deliver different characteristics of lightning activity, and none detect all of the lightning that occurs. This project focuses on combining the multi-instrument data into a single unified lightning product for potential use in operations. The resultant unified lightning product has the potential to simplify lightning data delivery, increase the amount of lightning activity represented, and provide value-added combinations of lightning flash properties available from individual data sources (e.g., flash size, frequency, and polarity) that inform about convective intensity. Prototype binary unified lightning grids are available to test as input for other products and algorithms, with ongoing development for real-time production. A follow-on project to prepare the unified lightning product for real-time deployment in the MRMS and operations has been proposed. Tangible outcomes from this project include 1 conference presentation. At present, there are no external partners, but proposed future work would include collaborations with NASA MSFC and UAH.

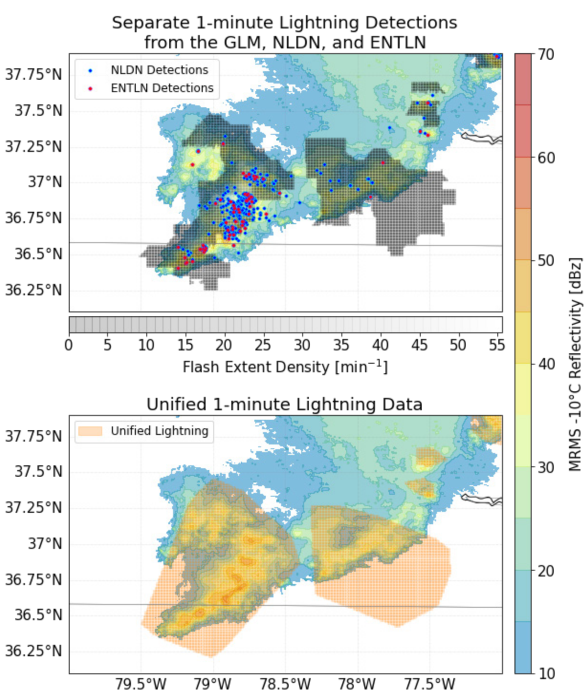


Figure 2-82: Three separate lightning datasets plotted over a 1-minute period, with MRMS -10°C reflectivity (color fill) for context (top). Conceptualization of mapped lightning activity from unified lightning data from three data sources over the same period (bottom).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Eric Bruning, Stephanie Weiss, David Singewald
Project Title: TTU support to GOES-R GLM cal/val and products
Relevance to NOAA: This project supports the NOAA mission by improving observation quality and stewardship, developing next-generation observational capabilities, and supporting the transition of infrastructure to cloud-based platforms.

This project supports the assessment of data quality and operational product processing for the GOES-R Geostationary Lightning Mapper, which recently launched its last two flight models on GOES-18 and -19. Texas Tech developed and provides ongoing support for the *glmtools* software package that converts Level 2 products into Level 3 imagery. These imagery products are now produced in the GOES ground system and delivered to NWS operations with the required latency and accuracy. The products have seen wider use in the community, including archival on NASA's EarthData portal and wider distribution by NSF Unidata, enabling display on popular websites such as the College of DuPage NEXLAB site. The TOWR-S group in NWS-OoO are using glmtools as a pathfinding algorithm for transition of the GOES Ground System and product delivery architecture to the cloud. Recent work with UAH also led to a calibrated GLM background product (essentially a new 777 μm full disk, 8 km visible imagery channel) that also enabled calculation of a data quality product to diagnose regions of degraded performance. These products were tested in the NSSL HWT. Efforts to understand GLM data quality were supported by funding to maintain, operate, and deliver data from the West Texas Lightning Mapping Array. This funding also facilitated coordination with EUMETSAT in support of their MTG Lightning Imager mission. Tangible outcomes from the product include 3 conference presentations, 1 algorithm in use in NOAA operations, 1 algorithm ready for operational transition, and 1 software release. 1 GRA was supported.

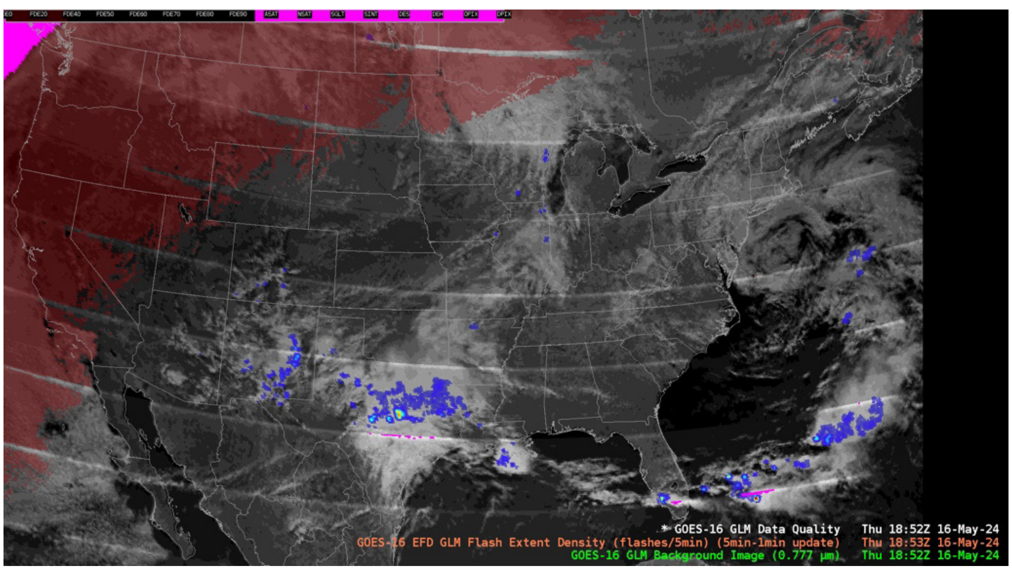


Figure 2-83: NWS AWIPS-II display of the GLM background (visible image), data quality, and flash extent density products at 1852 UTC 16 May 2024. Blue and yellow are lightning flashes observed by GLM. Pink shading shows saturated pixels, and red shading regions of low flash detection efficiency near the limb. All products use algorithms developed on this award.

CIWRO Themes: Weather Radar and Observations, Forecast Applications Improvements
CIWRO Contributors: Pierre Kirstetter, Shruti Upadhyaya
Project Title: Probabilistic quantitative precipitation estimation with geostationary satellites
Relevance to NOAA: This project supports the NOAA mission by creating/improving a trusted analysis of record for model verification/nowcasting

In this project a new decision-support capability for MRMS, the Probabilistic quantitative precipitation estimation with geostationary satellites, is created. Hydrometeorological applications require more than just one deterministic precipitation "best estimate" to adequately cope with the intermittent, highly skewed distribution that characterizes precipitation. This product is a gridded, CONUS-wide analysis of precipitation rates estimates that has a 5-min cadence and the horizontal resolution of the GOES-16 ABI sensor. The product includes both precipitation rates, uncertainties, and probabilities of exceeding thresholds for risk analysis. It is intended for nowcasting, post-event verification, and seasonal precipitation accumulations (Upadhyaya et al. 2022). A comprehensive analysis of retrievals shows that it provides better precipitation detection and quantification skills than the NOAA operational SCaMPR retrievals. Tangible outcomes from this project include 4 formal journal articles, 5+ conference presentations, and 1 algorithm considered for transition at NOAA/NESDIS and for the Integrated Multi-satellitE Retrievals for GPM (IMERG) developed at NASA. External partners involved in this project include NOAA National Environmental Satellite, Data, and Information Service, NASA Goddard Space Flight Center, and NASA Global Hydrometeorology Resource Center.

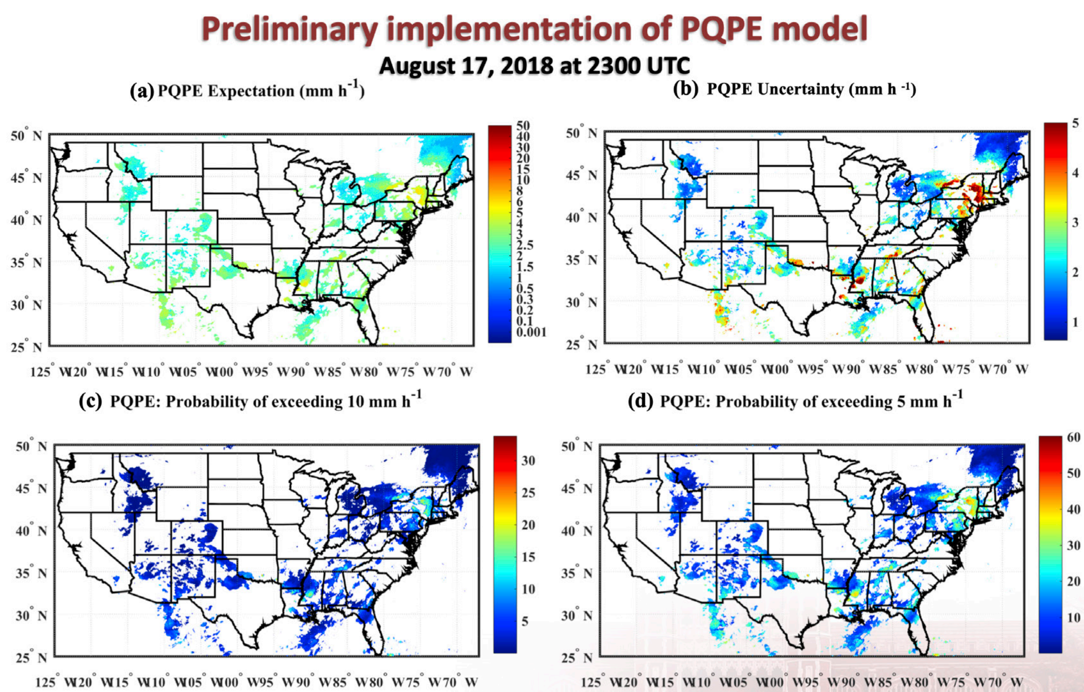


Figure 2-84: GOES-16 satellite based Probabilistic Quantitative Precipitation Estimation model products: (a) expectation; (b) uncertainty; (c) probability of exceeding 10 mm.h-1; (c) probability of exceeding 5 mm.h-1 on August 17, 2018 at 2300 UTC.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Ken Kehoe, Alyssa Sockol, Corey Godine, Mia Li, Randy Peppler
Project Title: Data inspection and assessment at the ARM DQO
Relevance to NOAA: NOAA scientists use ARM data for their research

The Atmospheric Radiation Measurement (ARM) Data Quality Office (DQO) oversees the data quality inspection, assessment, problem resolution, reporting, and documentation process to ensure that the data collected by the program are of the highest quality possible for research. Since October 2021, we have created 5 new platforms for data quality display, inspection, and assessment, resulting in a greater than 60% reduction in the number of days needed before data quality problem reports were resolved. Other tangible outcomes include an invited ARM/ASR PI Annual Meeting plenary talk in 2023 and numerous ARM/ASR meeting and workshop posters and presentations.

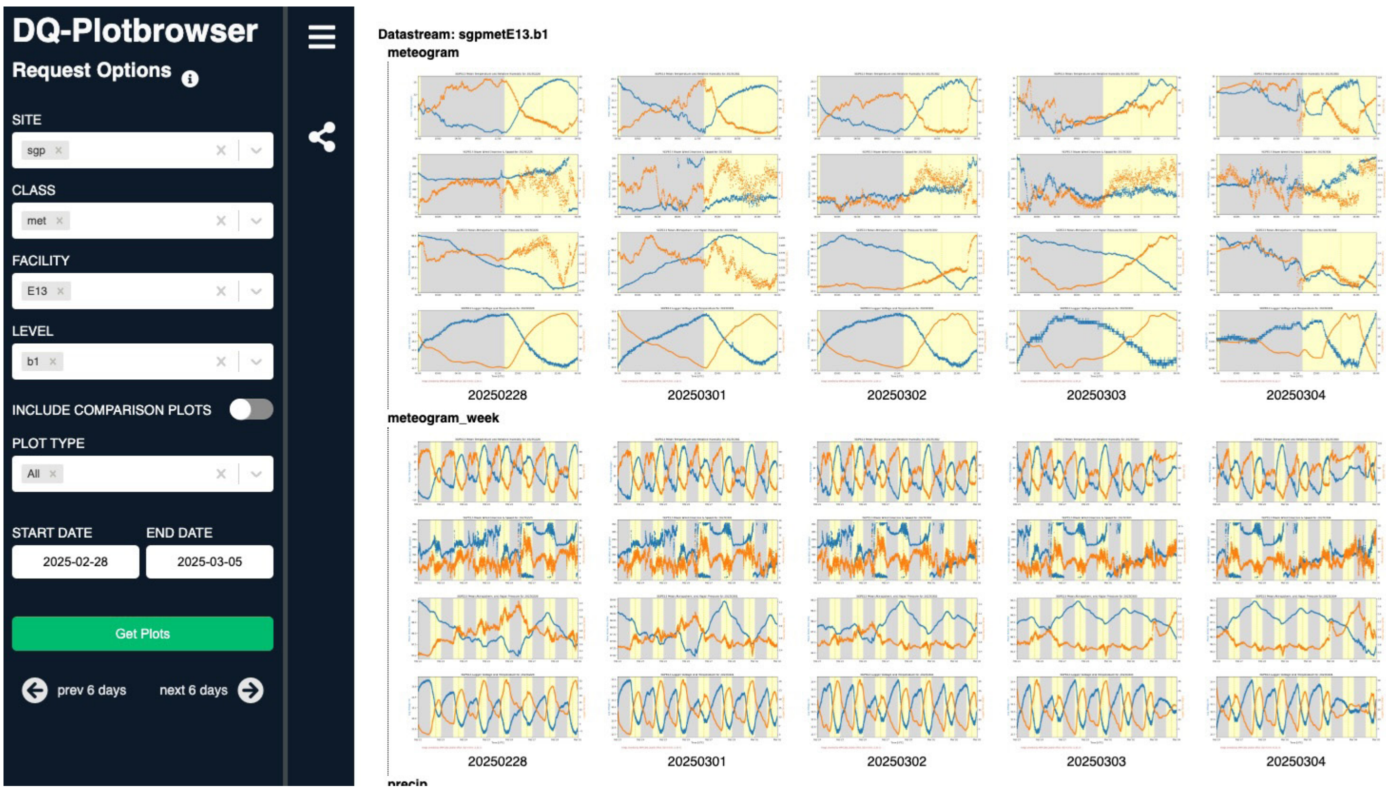


Figure 2-85: Example of new platform: DQ-Plotbrowser

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Alyssa Sockol, Ken Kehoe, Corey Godine, Mia Li, Randy Peppler
Project Title: ARM/DQP stakeholder interactions
Relevance to NOAA: NOAA scientists use ARM data for their research; ARM/ASR-funded scientists are located at NOAA labs and Cooperative Institutes

The ARM Data Quality Office interactions with ARM scientists and infrastructure aim to advance the scientific understanding of ARM instruments and data to scientific data users, as well as streamline the discovery, diagnosis, and resolution of data quality problems. Tangible outcomes since October 2021 include active participation at eight science and infrastructure working group meetings and the creation or update of more than 100 instrument software packages, including ARM mentor requests.

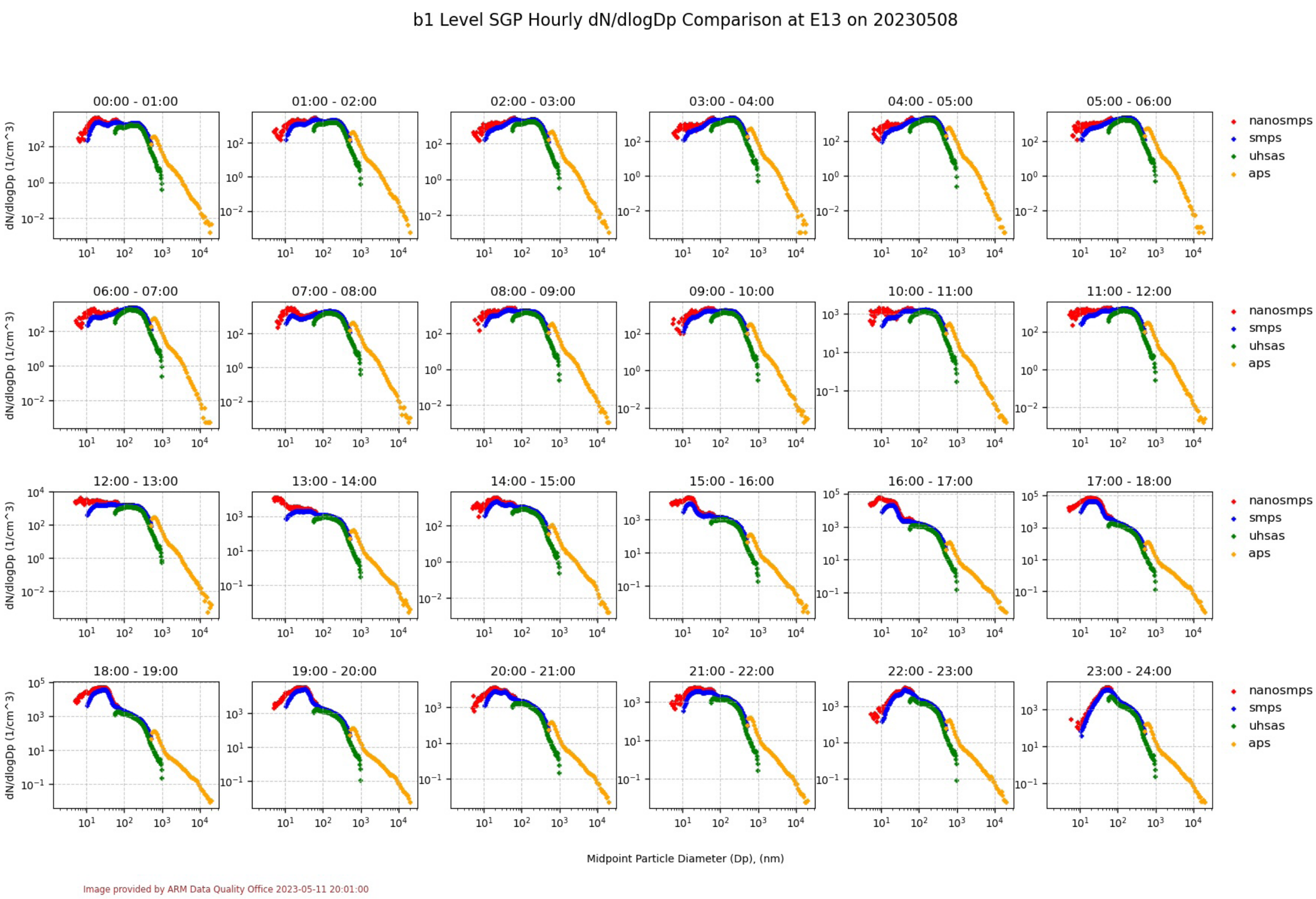


Figure 2-86: A comparison of differential number concentration of particles (dN) as a function of their logarithmic particle diameter (dlogDP), requested by an ARM mentor.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Ken Kehoe, Alyssa Sockol, Corey Godine, Mia Li
Project Title: Contributions to ARM open-source software repositories
Relevance to NOAA: NOAA scientists use ARM data for their research; ARM/ASR-funded scientists are located at NOAA labs and Cooperative Institutes

The ARM Data Quality Offices's significant contributions to ARM's open-source software repositories streamlines processes for scientific data users to explore, analyze, apply quality control, derive, and conduct research using ARM and also NOAA organization atmospheric data. Tangible outcomes since October 2021 have included 380 software commits to ACT (Atmospheric Community Toolkit, a Python library housing routines for working with atmospheric data) and 30 software commits to RadTraQ (Radar Tracking of Quality, a Python library housing routines related to assessing and monitoring radar data quality and calibration).

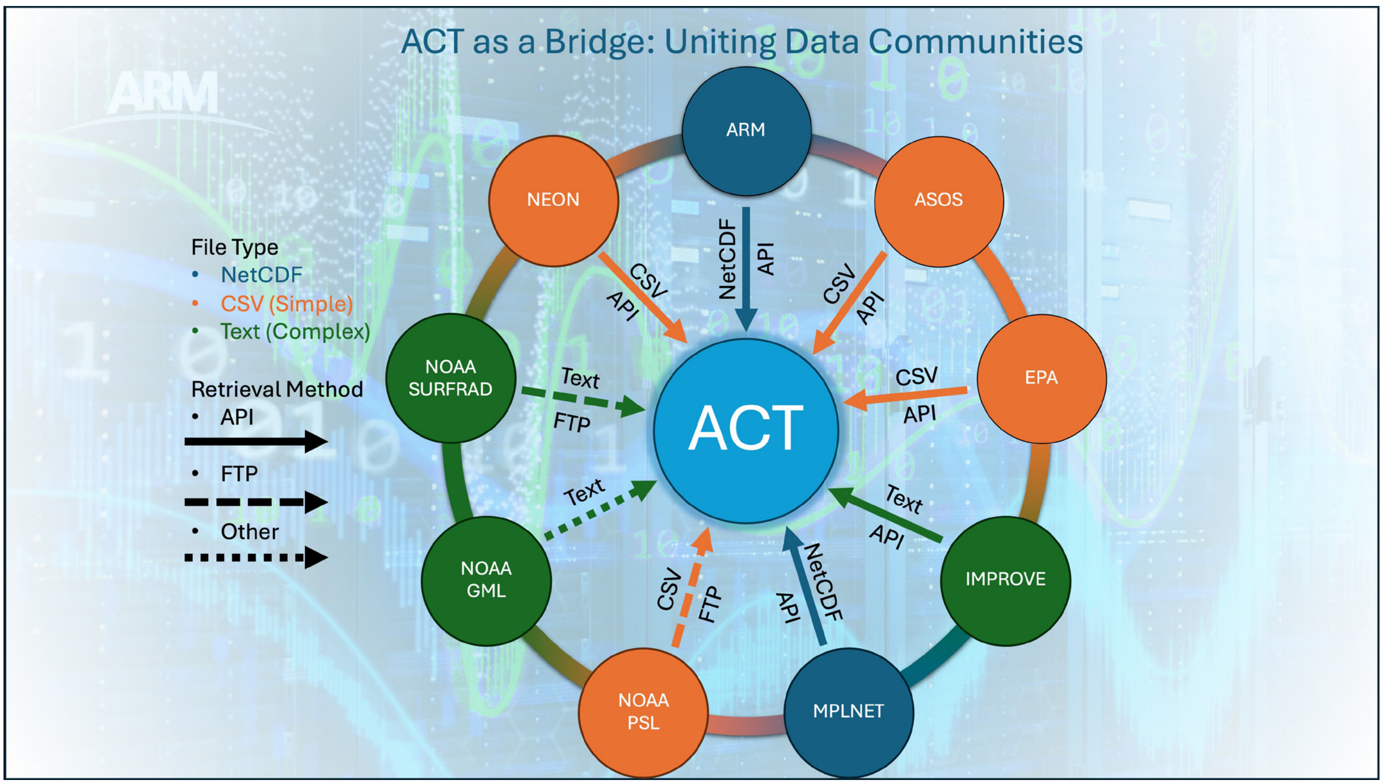


Figure 2-87: ARM's ACT program structure (top) and sample graphics for the Micropulse Lidar (bottom)." will also need to be updated to "ARM's ACT program structure

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Mia Li, Alyssa Sockol, Ken Kehoe, Corey Godine, Randy Peppler
Project Title: Now and the future - Assessing ARM data quality with AI
Relevance to NOAA: NOAA scientists use ARM data for their research; AI/ML is a major area of R&D within NOAA

The ARM Data Quality Office is developing advanced Artificial Intelligence (AI) algorithms to deliver continuous quality oversight of ARM data, empowering rapid actions to minimize the collection of poor data. This work began in spring 2023. Tangible outcomes so far include one peer-reviewed journal article and three conference presentations; an ARM toolkit is in development for 2025.

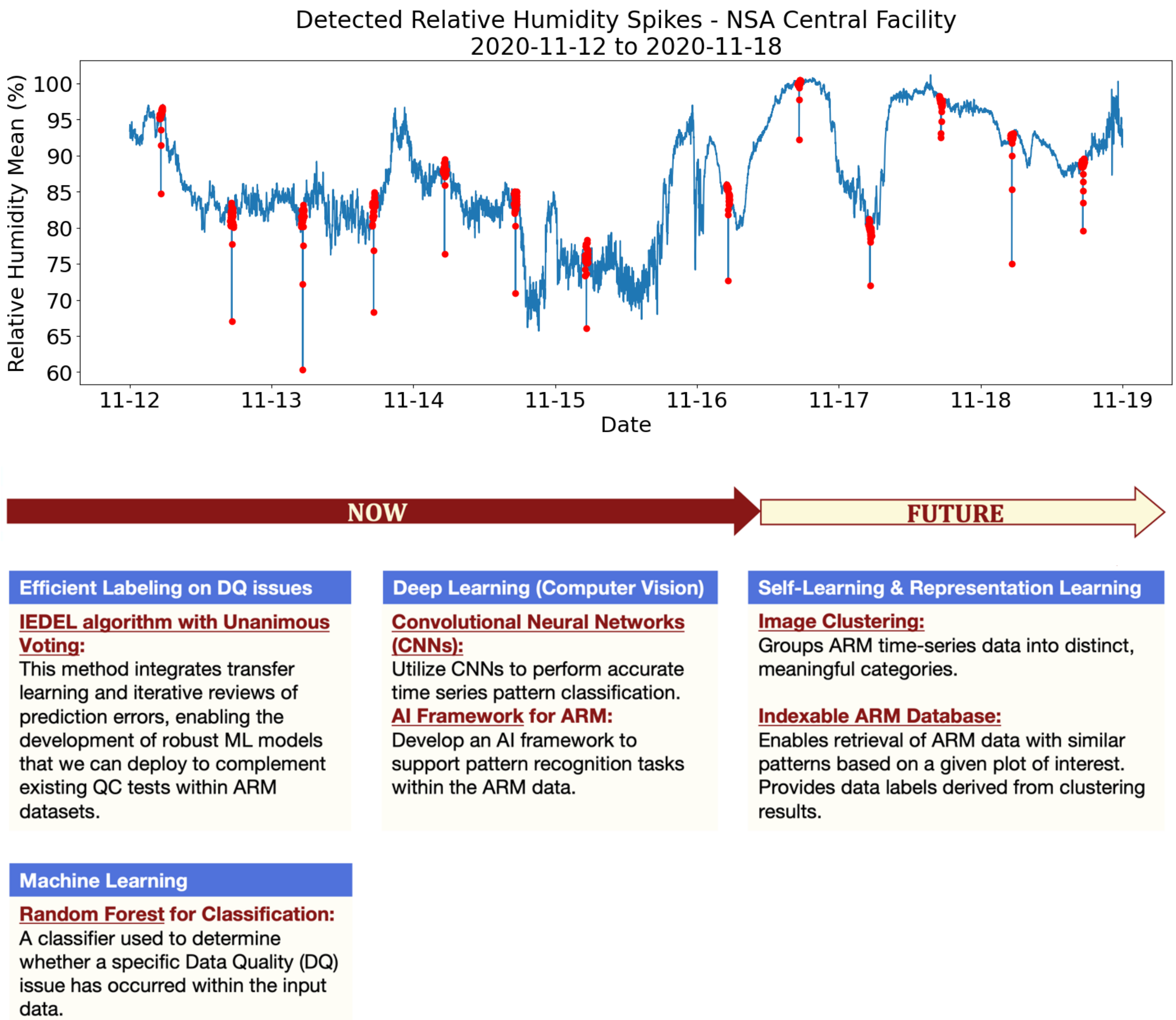


Figure 2-88: Early spike detection efforts (top) and a project planning schematic (bottom).

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Joshua Gebauer, Tyler Bell, Bobby Saba
Project Title: Developing an optimal estimation algorithm for wind profiling
Relevance to NOAA: This project supports the NOAA mission by optimizing platform agnostic data and information, improving observation quality and stewardship, and developing next generation observational capabilities.

This project developed an optimal estimation retrieval for wind profiling instrumentation called WINDoe. This retrieval enables more efficient use of wind profiling observations, increases the depth of the wind profiles retrieved from the instruments, and eliminates vertical data gaps that can occur. Another major benefit of this retrieval is that multiple wind profiling data sources can be used to create a combined profile that is more accurate than if only a single instrument or data source was used by itself (Gebauer and Bell 2024). WINDoe can be used with many types of wind profiling data and this retrieval may be a significant tool in future observing networks by providing a common retrieval format for the likely heterogeneous observing arrays that will make up our next-generation observation networks. This project produced 1 journal article, 2 conference presentations, and 1 published retrieval that has continued to be updated as the observation community identifies new needs and ideas.

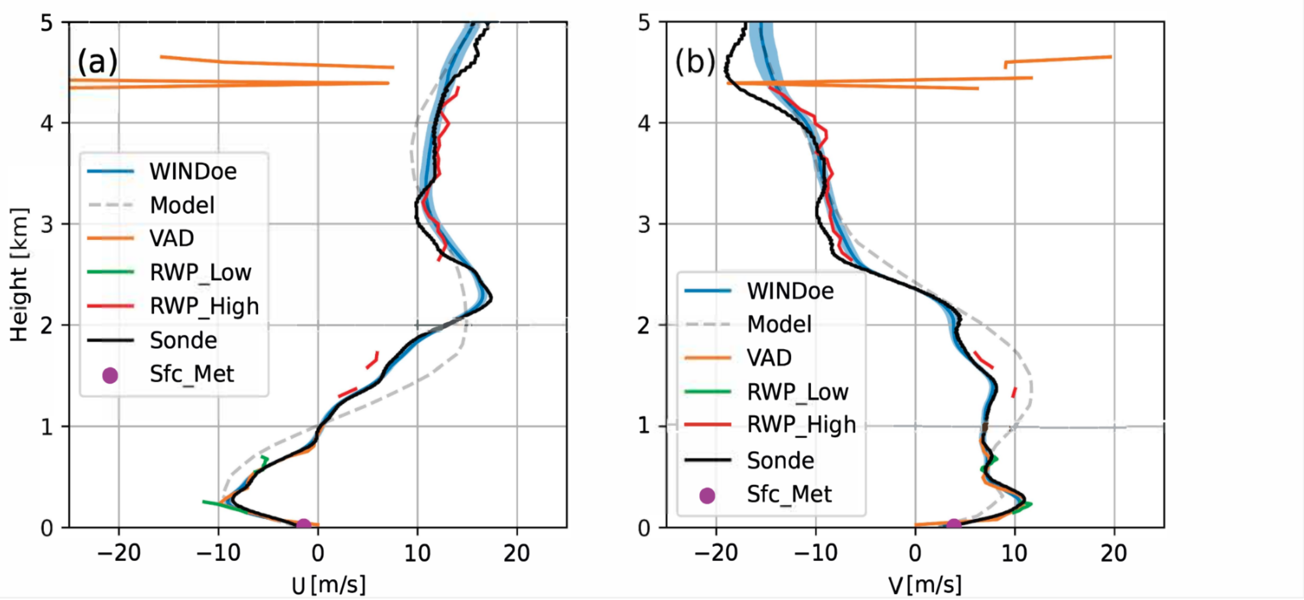


Figure 2-89: Retrieved (a) U and (b) V wind profiles for 7 May 2021 at 1135 UTC at the ARM SGP site for WINDoe retrievals that use lidar, radar wind profiler, surface meteorological station, and Rapid Refresh model profiles as input. WINDoe and the 1-sigma uncertainty of the retrieval are shown in blue. The individual instrument and model profiles and the reference radiosonde profile (black) are also shown.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Antonio Segales, Tyler Bell, Joshua Gebauer
Project Title: Progressive research and optimization of a durable and independent generation of uncrewed aircraft systems (PRODIGEE-UAS)
Relevance to NOAA: This project supports the NOAA mission by developing next generation observational capabilities.

This is a project funded by NOAA Office of Marine and Aviation Operations (formerly funded by the NOAA Uncrewed Systems Research Transition Office) to advance the CopterSonde UAS in such a way that it can be useful for severe weather research and operations. The CopterSonde is a weather-sensing UAS designed at OU and is being commercialized by InterMet Systems. It measures temperature, humidity, wind speed and direction, and pressure at high vertical resolution. Prior versions of the CopterSonde have been largely tailored for atmospheric boundary layer studies and has been shown to be one of the more accurate weather-sensing UAS in the research community (de Boer et al. 2024). PRODIGEE-UAS aims to increase the wind speed tolerance of the CopterSonde while maintaining the accuracy of previous versions. Evaluations since summer 2024 have shown that the new CopterSonde (CS-SWX) outperforms the prior version CopterSonde (CS-3D) in both thermodynamic (see Figure) and kinematic measurements. The new CoperSonde also has increased wind tolerance from 22 m/s to at least 32 m/s. An additional goal is achieving profiles up to 3 km above ground level, which additionally requires advancing ground station software to increase safety for beyond visual line of sight (BVLOS) operations. BVLOS flights are being coordinated in partnership with the Choctaw Nation of Oklahoma FAA Beyond program. To date, this project has resulted in a provisional patent application (#63/677,336) and has supported 1 MS and 2 UGRA students. The new CopterSonde design was unveiled in 1 conference presentation.

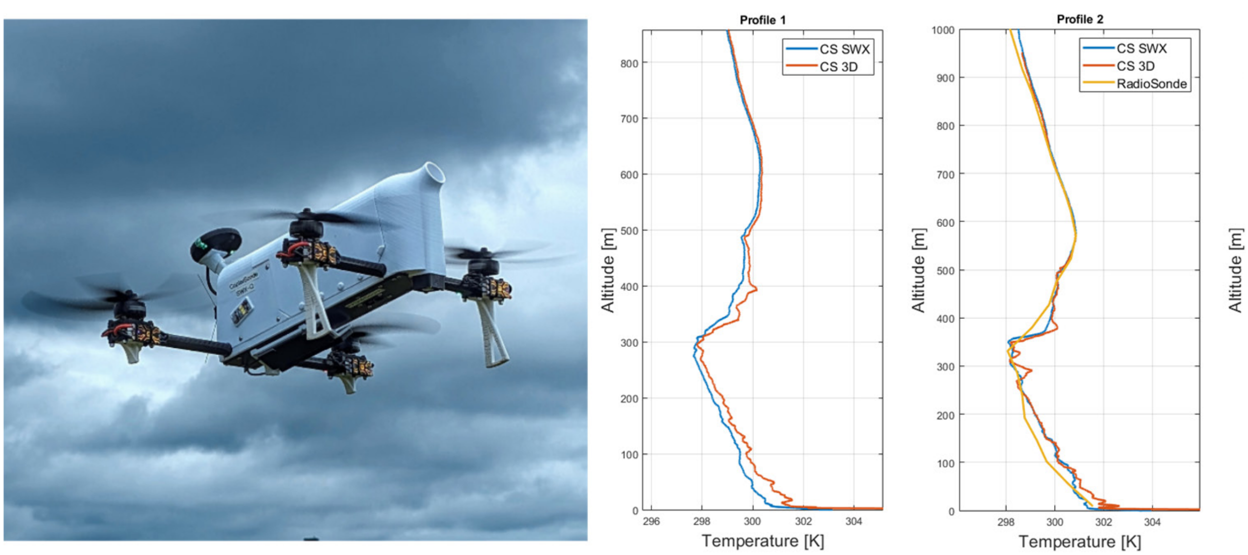


Figure 2-90: Example profiles collected by the new CS-SWX and the current CS-3D. The CS-SWX shows less noise in temperature measurements in low wind conditions (below the temperature inversion at ~300-400m) compared to the CS-3D. In the higher wind conditions above the inversion, the CS-SWX and CS-3D are identical.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Tyler Bell, Joshua Gebauer, Matthew Ammon, Lydia Bunting
Project Title: Propagation, evolution, and rotation in linear storms
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and developing next generation observational capabilities.

The Propagation, Evolution, and Rotation in Linear Storms (PERILs) project was a large, multi-institution field project to observe southeast United States tornadic environments with a focus on tornadoes during linear convective events, which prior to this project have been understudied. As part of this two-year field campaign, our team deployed the Collaborative Lower Atmosphere Mobile Profiling Systems (CLAMPS) at two locations in the Mississippi Delta region during the southeast severe weather season and flew three CopterSonde UAS systems up to 1500 m simultaneously at three locations during Intensive Operation Periods (IOPs). Initial analysis of tornadic storms during the field project identified that there was a maximum of occurrence near the western edge of the Mississippi Delta. Observations from this field project identified that the PBL characteristics of the mid-Delta region at Lake Village, AR and the edge of the Delta at Yazoo City, MS were significantly different, with the Yazoo City, MS site experiencing more turbulence and terrain induced vertical motions. The low-level wind profile at the Yazoo City site was also more favorable for tornadic thunderstorms (Ammon et al. 2024). These observations suggest that the terrain and vegetation gradient near Yazoo City, MS may produce more favorable conditions for tornadogenesis. This project produced 1 journal article that is currently under review, 2 conference presentations, and 10 published datasets. This project also supported 2 undergraduate researchers

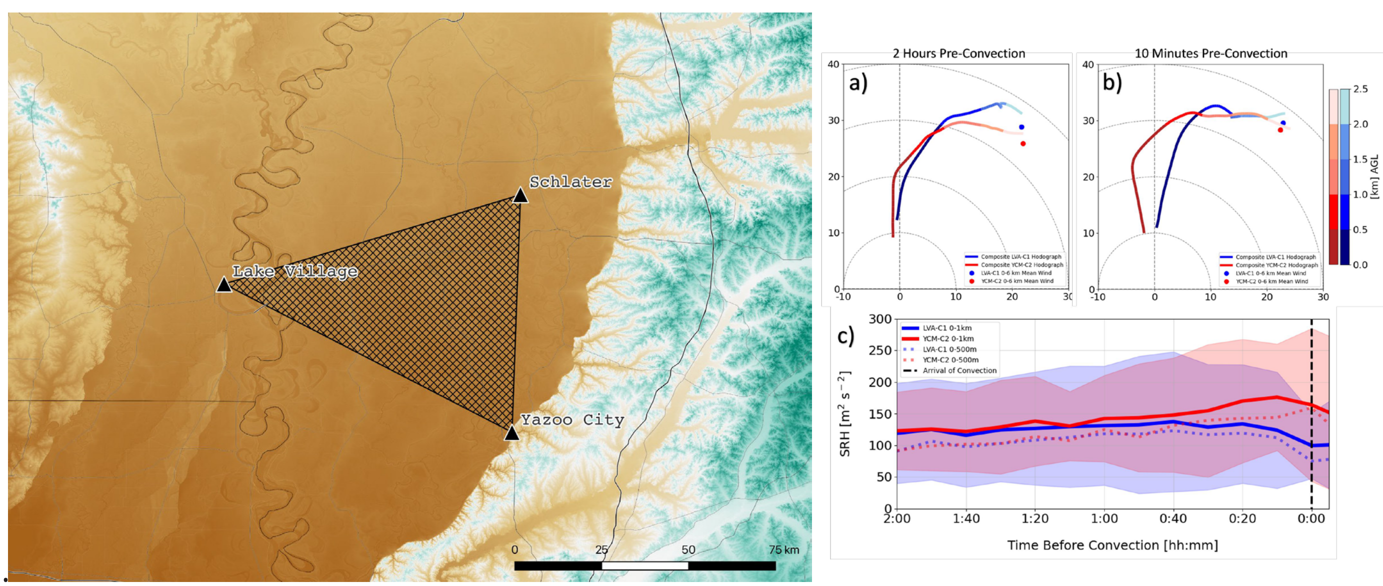


Figure 2-91: (Left) Location of the observation sites during the PERILs project and (right) composite wind profiles from at these locations (a) 2 hours pre-convection and (b) 10 minutes pre-convection. The storm relative helicity time series at the locations is shown in (c).

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Joshua Gebauer, Tyler Bell, Lydia Bunting
Project Title: The American wake experiment (AWAKEN)
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions, and developing next generation observational capabilities.

The American WAKE experimeNt (AWAKEN) is a large international field project led by the Department of Energy to observe wind farm wake interactions. CIWRO assisted in this project by deploying the two CLAMPS systems over two periods in 2022 and 2023. The CLAMPS systems were deployed at a near-wind farm and far-wind farm location to examine how the wind farm wakes impact boundary-layer development. Initial analysis of the data from these deployments has identified stronger low-level mixing at the near-wind farm site (Jordan et al. 2024). Understanding how wind farms impact the boundary layer and how these boundary layer modifications affect convection initiation is critical as the area covered by wind farms continues to grow. This project has produced one published journal article, two conference presentations, and 9 published datasets. The project supported one Ph.D. student and collaborators include the National Renewable Energy Laboratory, Pacific Northwest National Laboratory, Lawrence Livermore National Laboratory, Argonne National Laboratory, Sandia National Laboratory, University of Colorado at Boulder, University of Texas at Dallas, and Cornell University.

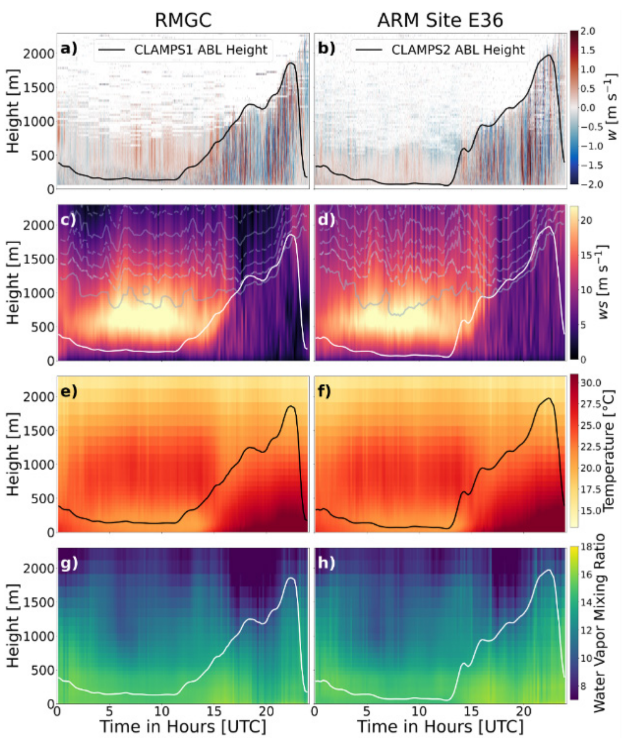


Figure 2-92: CLAMPS data on September 23, 2023 for the two sites of interest: lidar w (a and b), lidar ws retrievals from WINDoe, AERI temperature retrievals (e and f), and AERI water vapor mixing ratio retrievals (g and h); these profiles were retrieved using TROPoe. The ABL height is overlaid as a heavy line (white or black). This parameter is retrieved by the fuzzy logic method using a combination of CLAMPS data from the respective site.

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Joshua Gebauer, Tyler Bell, Bobby Saba
Project Title: Examining surface layer vertical vorticity structures during the low-level internal flows in tornadoes experiment (LIFT)
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions

During the Low-Level Internal Flow in Tornadoes field project, a Doppler lidar was used to identify if coherent streaks of vertical vorticity were present in the near inflow of supercell thunderstorms. Coherent streaks of vertical vorticity have been found in a recent modeling study to serve as genesis points for tornadoes. The confirmation of these streaks in the near-inflow of supercells would provide evidence that processes found in these modeling studies may be occurring. In the first year of the field campaign, these surface layer vorticity streaks were found interacting with the outflow boundaries of the supercell. While no tornado was observed with the lidar in the first year of the field deployments. The confirmation of these surface layer vorticity structures motivates more observations of these structures around potentially tornadic thunderstorms and further research into the environments that are favorable for their development. This unique use of Doppler lidar has also led to the development of advanced spectral processing techniques to improve the maximum range of the lidar. This ongoing project has so far resulted in 1 conference presentation.

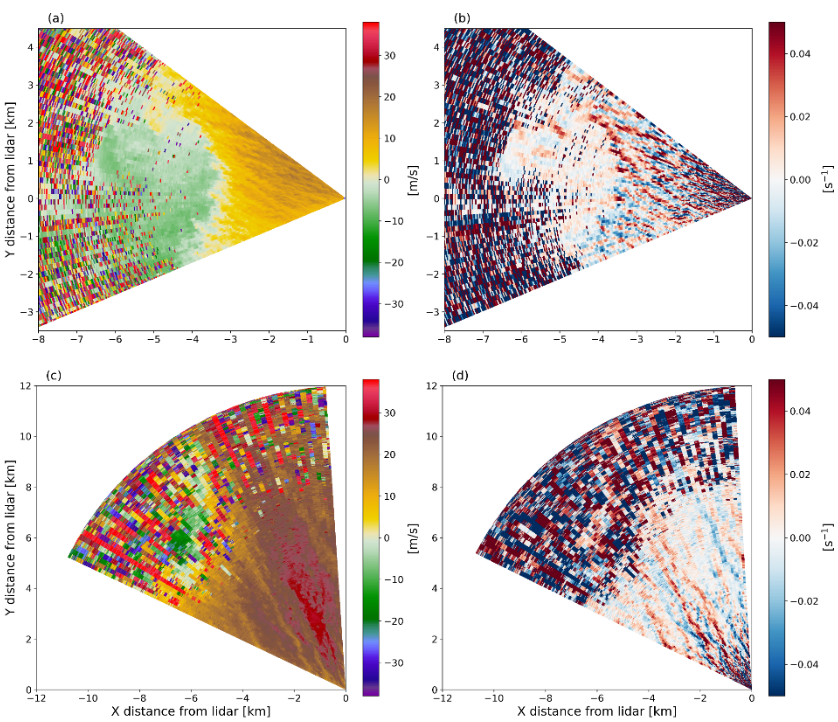


Figure 2-93: Radial velocity (a,c) and inferred vorticity due to azimuthal shear (b,d) from the NSSL Doppler Lidar Truck observing the near-inflow region of supercells on 2 May 2024 at 1 deg elevation (a,b) and 24 May 2024 at 0 deg elevation (c,d).

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Tyler Bell, Joshua Gebauer, Lydia Bunting
Project Title: Tracking aerosol convection interactions experiment (TRACER)
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions

The Tracking Aerosol Convection interactions ExpeRiment (TRACER) aimed to observe convective clouds in high spatial and temporal resolution in and around the Houston, TX metro area. The Department of Energy Atmospheric Radiation Measurement (DOE ARM) program deployed an ARM Mobile Facility (AMF) for this campaign. CIWRO contributed to two sub-campaigns: TRACER-UAS and TRACER-CUBIC. TRACER-UAS, in partnership with the University of Colorado Boulder, deployed weather sensing UAS near the Gulf Coast to collect high resolution data of the atmospheric boundary layer thermodynamic and aerosol conditions that drive the formation of convective cells. The CopterSonde UASand the RAAVEN UAS both deployed for a combined 200 flight hours from 1 June and 30 September 2022 (Lappin et al. 2024). The Coastal Urban Boundary-layer Interactions with Convection (CUBIC) campaign deployed 2 Collaborative Lower Atmospheric Mobile Profiling Systems (CLAMPS) and, in partnership with the University of Wisconsin Madison, the Space Science and Engineering Center Portable Atmospheric Research Center (SPARC) facility. This project aimed to extend the AMF with similar remote sensing to cover more of the Houston area. CIWRO supported this project through new developments on the TROPoe retrieval algorithm and processing the data from these three systems to be in line with ARM standards. The new developments needed for TROPoe to account for the high moisture content in the Houston metropolitan area has also led to improved retrievals for other field deployments of CLAMPS. These campaigns produced 14 published datasets, supported 2 PhD students, produced 2 publications, with 1 additional publication in review.

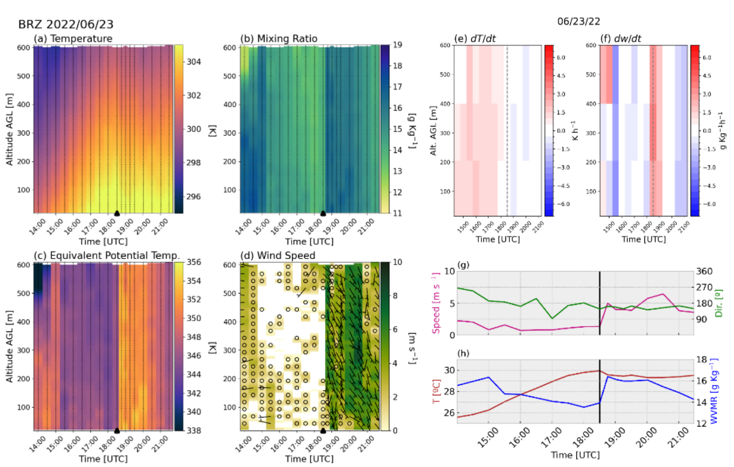


Figure 2-94: CopterSonde observations from 23 June 2022 at Brazoria National Wildlife Refuge. (a) temperature (K), (b) water vapor mixing ratio (g kg−1), (c) equivalent potential temperature (K), (d) wind speed (m s−1) with wind barbs overlaid, (e) temperature rate of change (dT/dt, K h−1), (f) water vapor mixing ratio rate of change (dw/dt, g kg−1 h−1), (g) profile averaged wind speed (pink) and direction (green) time series, (h) profile averaged temperature and dewpoint (ºC) time series. Black carets in subplots a-d, dashed lines in e-f, and solid black lines in g-h indicate the SB

CIWRO Themes: Weather Radar and Observations, Forecast Applications Improvement
CIWRO Contributors: Martin Satrio, Elizabeth Tirone, Dominic Candela
Project Title: Harnessing UAS and high-resolution satellite imagery to better characterize wind damage and understand tornado behavior
Relevance to NOAA: This project supports the NOAA mission by utilizing observation instruments and techniques to better understand tornado behavior and resultant damage.

Quantification of near-ground wind speeds in tornadoes continues to be a challenge within the meteorology and engineering community, but one that is necessary to address to continue meeting the needs of protecting life and property. Current methods to measure and estimate tornadoes and wind speeds have serious limitations — this is especially true when coupling the Enhanced Fujita scale which uses maximum damage as a proxy to wind speed, with tornadoes that impact only rural areas and / or vegetation. To attempt to address this problem, this project uses NSSL and CIWRO employed UAS technologies and specialized satellite imagery to assess storm damage through finescale mapping of wind damage *immediately* following storm effects. In total, NSSL-CIWRO led 48 UAS-damage assessments from 2021 to 2023. These were geographically and geologically-diverse missions, with locations covering the Northern High Plains to the Gulf Coast and encompassing a variety of land cover and terrain. In doing so, we aim to improve our understanding of tornado dynamics as it relates to heterogeneous land cover and terrain, especially regarding the very-near ground wind damage. In addition, post-event UAS and satellite imagery collected as part of the missions were rapidly disseminated to operations, shared to both NWS Weather Forecast Offices and to the Federal Emergency Management Agencies to improve official post-event damage assessments. Overall, these products have been an important addition to traditional ground- and satellite-based surveys. This work has supported 2 UGRAs and 1 GRA, and has resulted in one journal article published in BAMS (Wagner et al. 2024) and 7 conference presentations.

Figure 2-95: High-resolution imagery from the 24 March 2023 EF4 Rolling Fork, MS tornado. a) Skysat 50 cm 469 imagery. Yellow outlined boxes correspond to b-c) 3 cm UAS orthomosaics obtained from NSSL fixed-wing 470 UAS, highlighting detailed treefall and ground markings (deposition).

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributor: Elizabeth Tirone
Project Title: Automated treefall detection using machine learning
Relevance to NOAA: This project supports the NOAA mission by improving observation quality.

Imagery was collected by uncrewed aircraft systems (UAS) for numerous tornadoes from 2021-2024. This high-resolution imagery provides numerous avenues for analysis into near surface tornado behavior; however, the vast size of this data presents a major challenge. Machine learning (ML) is an important tool to improve the efficiency to evaluate this data, but ML has its own limitations, mainly due to the amount of labeled data required for most applications. Zero-shot ML was tested in its ability to automatically and semi-automatically generate training labels to use in further ML implementations. This method was shown to be upwards of ten times faster than labeling data by hand while still producing high enough output to be used in an object detection ML model to detect fallen trees. This project is ongoing and has resulted in two conference presentations. Zhiang Chen at the California Institute of Technology has collaborated on this project.

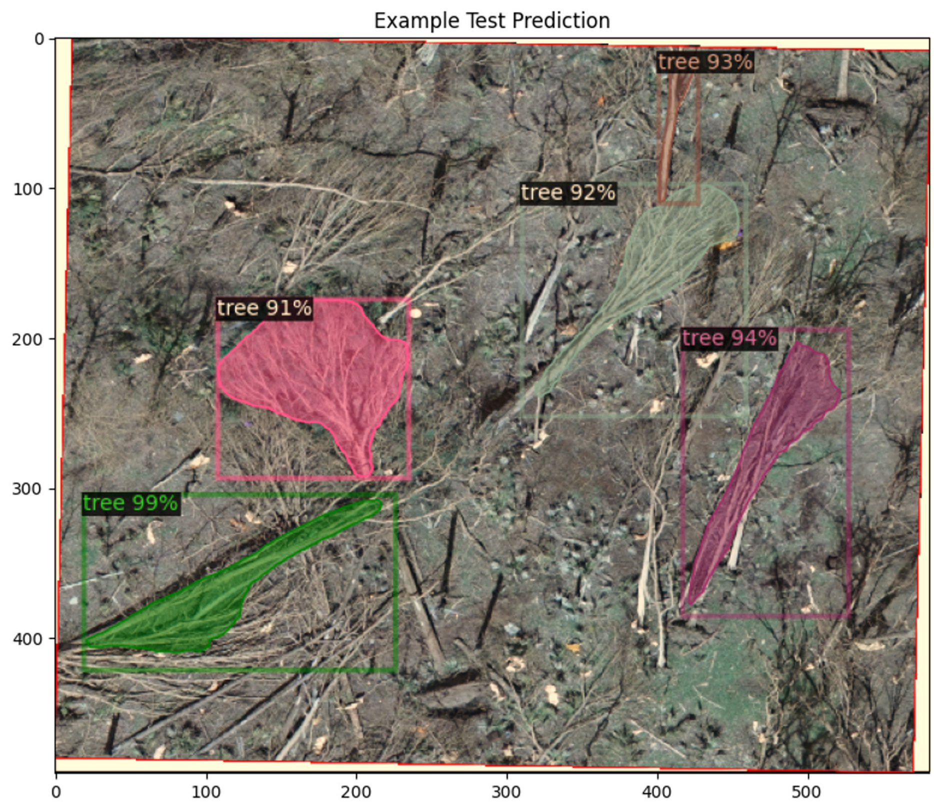


Figure 2-96: Example machine learning prediction for object detection. Colored masks represent predicted tree area, the corresponding colored box depicts the predicted object detection bounding box, and the percentages are a representation of machine learning confidence.

CIWRO Themes: Weather Radar and Observations, Mesoscale and Stormscale Modeling
CIWRO Contributors: Martin Satrio, Dan Stechman, Patrick Skinner, William Faletti, Kent Knopfmeier
Project Title: Investigating the 23 May 2022 supercell through an innovative analysis of targeted observation by radars and UAS of supercells (TORUS) observations
Relevance to NOAA: This project supports the NOAA mission by improving understanding of severe convective storms and supercells through novel modeling approaches, data assimilation, and observational platforms from the TORUS campaign.

The Targeted Observations by Radar and Unmanned Aerial Systems (TORUS) field campaign observed a cyclic, tornadic supercell on 23 May 2022. The supercell was extensively sampled using a variety of radar platforms and in-situ instruments including dual-radars on the P-3 aircraft, the NSSL X-band polarimetric mobile radar (NOXP), two Ka-band mobile radars operated by Texas Tech, and two WSR-88Ds (KFDX and KLBB). This project uses a blend of innovative analysis techniques to investigate the internal supercell dynamics as well as the noteworthy modification of the supercell to its surrounding environment. QC'd radar data were synthesized into 30 independent multi-Doppler wind syntheses over four hours. Our findings reveal storm-scale processes crucial to the supercell's evolution, such as continuous cell mergers and their impact on updraft dynamics. We observed two significant rightward deviations, with each shift coinciding with intense tornadic periods well-captured by the three-dimensional kinematic fields. Along with multi-Doppler analysis, we utilize a data assimilation analysis approach with a modified version of the WoFS workflow. Preliminary WoFS analyses assimilating WSR-88D and surface observations suggest accurate depiction of storm-scale features, generally small environmental errors, and similar horizontal wind retrievals to multi-Doppler analyses. Further development of this system to assimilate TORUS observations will be conducted, and intercomparison with multi-Doppler syntheses will be performed. This work has resulted in two conference proceedings and support of one GRA.

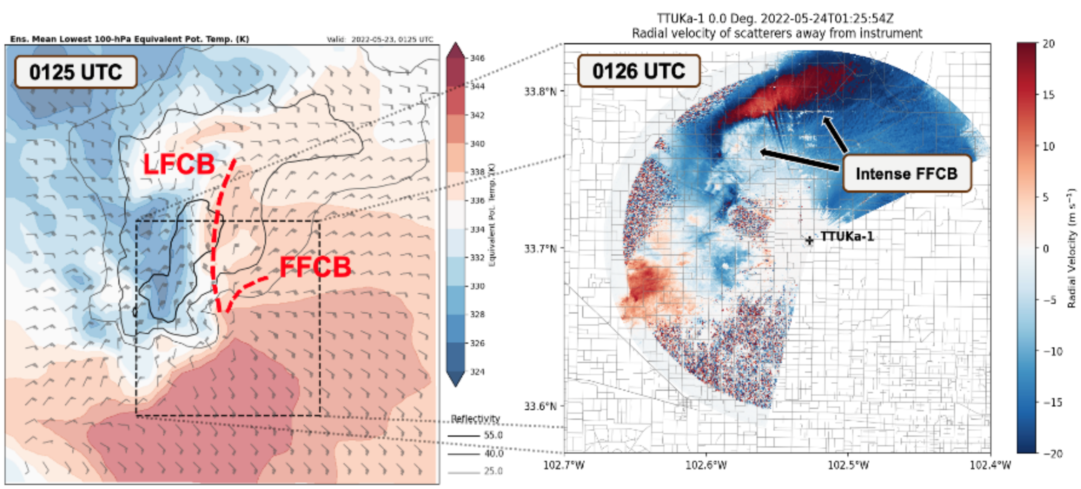


Figure 2-97: WoFS analyzed theta-e and 10 m winds with annotated left- and forward-flank convergence boundaries (LFCB & FFCB; left) and TTUKa1 radial velocity (right), suggesting accurate depiction of observed FFCB. Both valid ~0125 UTC 24 May 2022.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Bobby Saba, Josh Gebauer, Tyler Bell
Project Title: Examining supercell environments with doppler wind LiDAR observations
Relevance to NOAA: This project supports the NOAA mission by utilizing improvements in observational platforms and post-processing techniques to analyze supercell environments in a novel fashion.

This project utilized Doppler wind lidar observations from various collaborative field efforts (mini-MPEX, TORUS, and TORUS-LiTE). The research goal of this instrument is to observe the evolution of storm inflow properties to gain a better understanding of the storm environment surrounding an evolving supercell. A new optimal estimation technique (windOE) was incorporated to assimilate co-located rawinsonde and surface observations into the wind retrievals that provide data between the surface and 75m. These observations are used to validate the post processing techniques and output will be compared to previously used methods. Focus was placed on the evolution of the near-ground kinematic characteristics and the storm induced environmental modification in storm environments. Key findings include similarities in the low-level storm-relative flow fields in each composite and greater streamwise *and* crosswise vorticity in tornadic storm environments in the surface layer. This work resulted in 4 conference presentations and 1 GRA was funded on this work.

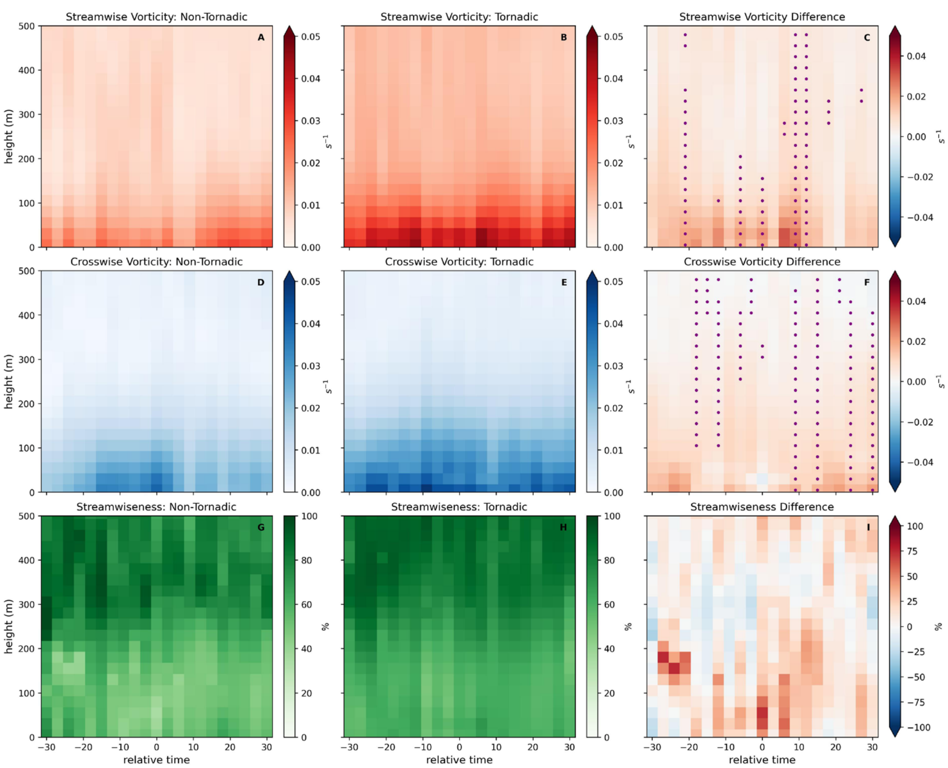


Figure 2-98: Difference in horizontal streamwise (top) and crosswise (middle) vorticity and the ratio of streamwise vorticity to total horizontal vorticity (bottom) between tornadic (left) and non-tornadic (right) composite supercell environments in time. Plots show the surface to 500 meters above ground level.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributor: Dan Stechman
Project Title: Leveraging multi-Doppler observations to improve our understanding of quasi-linear convective systems in the Southeast US
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions, and by developing next-generation observational capabilities.

Tornadoes within quasi-linear convective systems (QLCSs) account for more than a fifth of all tornado reports in the US, though there is a dearth of observational studies of these phenomena and their parent mesovortices. Apart from spawning tornadoes, QLCS mesovortices can contribute to the enhancement of severe straight-line winds. On 30 April 2017, during the VORTEX-SE field campaign, the NOAA P-3 airborne Tail Doppler Radars (TDRs) sampled an extensive QLCS as it progressed through Alabama, with complementary observations gathered from the NWS Hytop, AL WSR-88D (KHTX), and an OU Shared Mobile Atmospheric Research and Teaching Radar (SMART-R 2). Airborne and ground-based radar observations spanning nearly 2.5 hours have been incorporated into three-dimensional wind syntheses, revealing mesovortices of various scales, one of which persisted through much of the analysis period. One potential mechanism responsible for the formation and maintenance of QLCS mesovortices is the release of horizontal shear instability (HSI). Significantly expanding on the work of Conrad and Knupp (2019), this study evaluated two stability criteria—Rayleigh and Fjørtoft—at many different times and locations within the QLCS. For this particular system, both the Rayeigh and Fjørtoft stability criteria were satisfied in every instance, regardless of whether an existing circulation was present or not. This suggests that the release of HSI was likely a factor in mesovortexgenesis, but similar studies across multiple systems will be required to elucidate the ubiquity of HSI in QLCSs occurring in the southeast US.

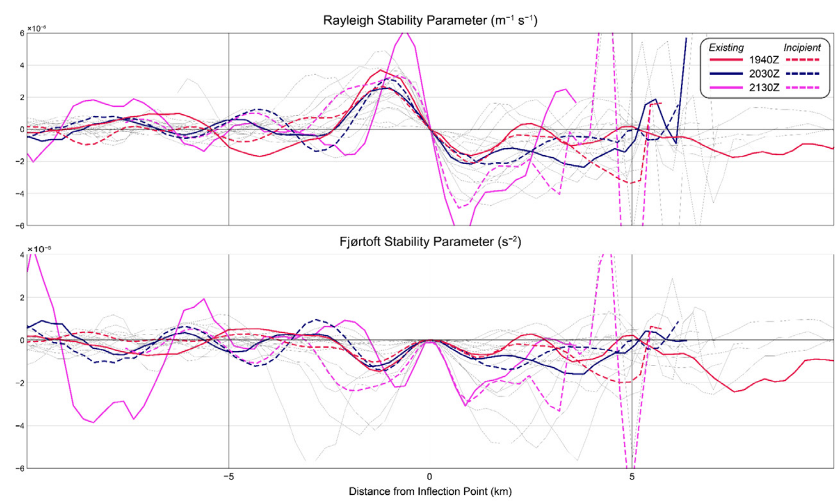


Figure 2-99: Rayleigh (top panel) and Fjørtoft (bottom panel) instability parameters assessed at numerous times both in the vicinity of existing (solid colored traces) and incipient (dashed colored traces) circulations, all relative to the inflection point in the wind field. The Rayleigh criteria is satisfied for HSI when values are positive behind the inflection point and negative ahead, while the Fjørtoft criteria is satisfied when values are negative immediately to either side of the inflection point. Light gray traces represent all evaluated portions of the system.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributor: Dan Stechman
Project Title: Improving our understanding of supercells from convection initiation to tornadogenesis via innovative observations, simulations, and analysis techniques
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions, and by developing next-generation observational capabilities.

The Targeted Observations by Radars and Unmanned Aircraft Systems of Supercells (TORUS) experiment collected airborne and ground-based radar observations of a long-lived tornadic supercell from multiple platforms on 20 May 2019. The supercell initially produced several brief, weak tornadoes, followed by an EF-2 tornado that did damage in Mangum, OK. The NOAA P-3 research aircraft with its forward and aft-angled X-band Tail Doppler Radars (TDRs) completed 20 observational flight legs ahead of the storm over 3 hours. A Texas Tech University Ka-band and the NSSL NOXP X-band mobile radars provided valuable collocated observations of the storm, enabling more accurate, close-range quad-Doppler supercell analyses spanning five volumes up to and through tornadogenesis time. A key highlight includes the 3-D radar wind syntheses spanning nearly 2 hours prior to the EF-2 tornado, complete with documentation of the impacts of a cell-merger immediately preceding tornadogenesis. In particular, it was found that the vertical vorticity associated with the low-level mesocyclone was significantly disturbed and initially weakened by the cell merger, along with an overall broadening of the low-level updraft area. Immediately following the merger, the updraft consolidated and intensified and vertical vorticity increased significantly. Work is ongoing to identify inflow source regions and to define the evolving character of the various surface-based internal storm boundaries. This work has resulted in one conference presentation.

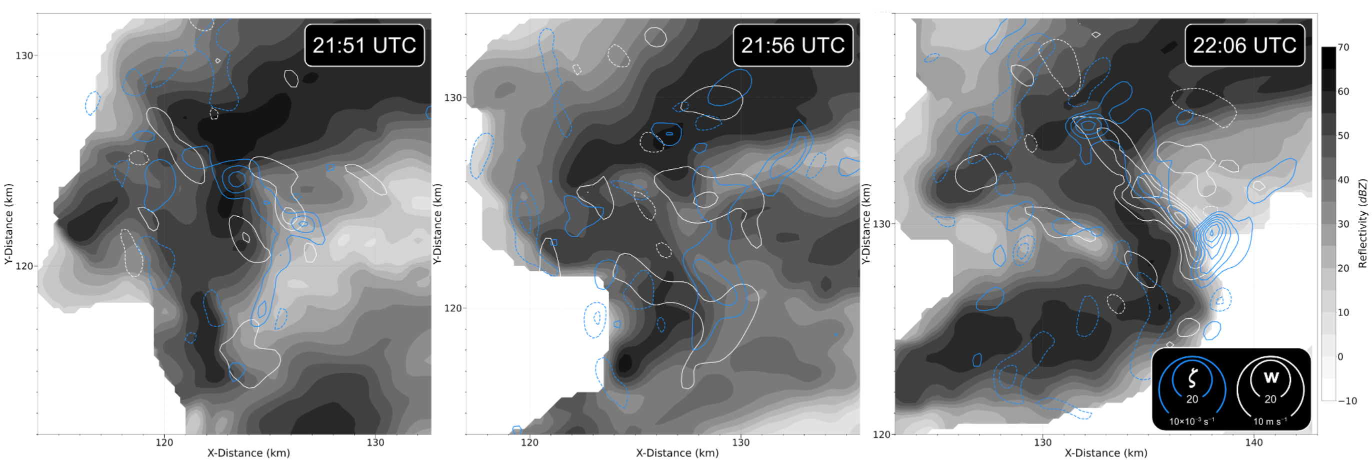


*Figure 2-100: Observed supercell-cell merger with radar reflectivity (grey shading) and vertical vorticity (**ζ**; blue contours) at 250 m AGL, and vertical velocity at 1 km AGL (W; white contours) between 21:51 and 22:06 UTC on 20 May 2019, near Mangum, OK.*

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Martin Satrio, Dan Stechman
Project Title: Low-level mesocyclone evolution of a cyclic tornadic supercell observed during TORUS on 17 May 2019
Relevance to NOAA: This project supports the NOAA mission by advancing understanding of supercell and tornado dynamics using a suite of observing platforms from the TORUS campaign.

This work presents a case study on the 17 May 2019 cyclic, tornadic supercell from southwest Nebraska observed by the Targeted Observations by Radar and UAS of Supercells (TORUS) field experiment. Specifically, 12 multi-Doppler wind syntheses which retrieve the three-dimensional wind field are generated over a 96-min period, using two P-3 airborne radars and the ground-based NOXP research radar. The multi-Doppler results are then further assimilated into a diabatic Lagrangian analysis (DLA) to retrieve three-dimensional thermodynamic data such as temperature and moisture. The retrieved wind fields correlate well with observed tornadic and non-tornadic periods, and several storm-scale features related to low-level rotation processes are documented. This includes vortex line arches that are a defining feature during the first EF-2 tornado. During the most active tornadic period, the source region of air participating in the core of the rotation is found to be both internal and external to the storm itself. With source air internal to the storm, internal buoyancy gradients play a large role in generating horizontal rotation, which is then tilted into the vertical. This process resembles streamwise vorticity currents (SVCs) that are important in numerical simulations. Overall, the 96 min analysis period with 4D kinematic and thermodynamic data makes this study one of the most detailed supercell case studies presented in the literature. This work has resulted in four conference presentations and one journal article in MWR (accepted pending minor revisions; Satrio et al. 2025). This work has also supported one GRA now transitioned to a CIWRO postdoc (Martin Satrio).

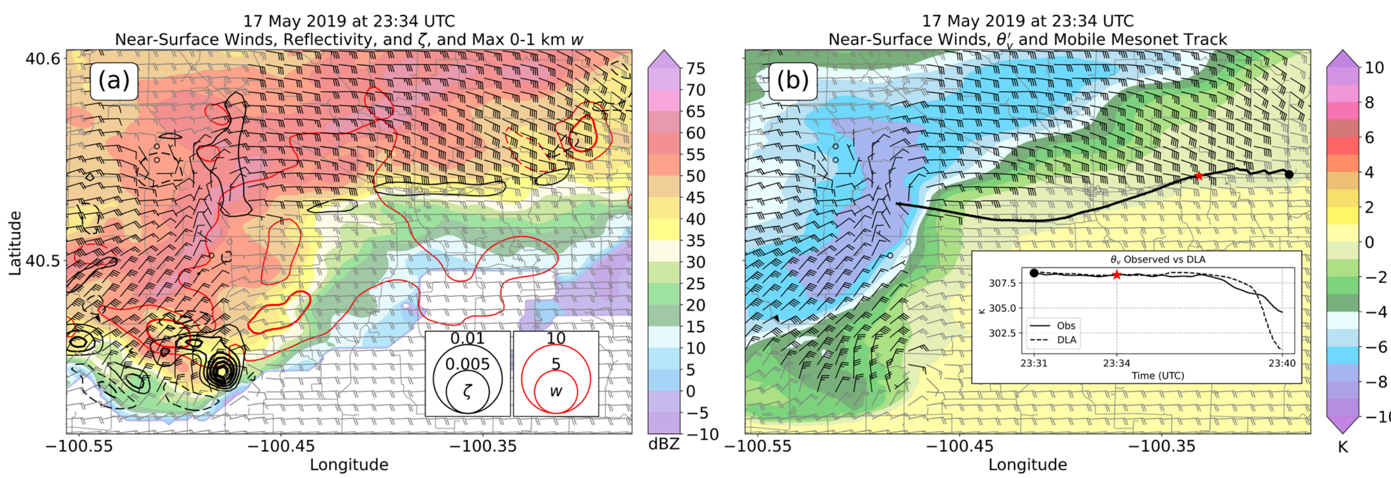


Figure 2-101: Shaded reflectivity with contoured surface vertical vorticity (black) and maximum 0-1 km AGL vertical velocity (red). (b) Shaded surface θ_v' with mesonet track in the black line. The inset plot shows the observed θ_v (solid line) versus the θ_v derived from the DLA (dashed line).

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributor: Madeline Diedrichsen
Project Title: Testing the usability of Sparv Windsonds in convective environments
Relevance to NOAA: This project supports the NOAA mission by improving observation quality and developing next-generation observational capabilities.

Windsonds are a relatively new sounding system that has been used by CIWRO and NSSL in the last five years, but little has been done to understand how Windonds can be quality controlled and analyzed with other sounding systems. This project aimed to quantify the differences between two sounding systems to better inform the future analysis of Windsonds, specifically in convective research. All 470 Windsonds launched during TORUS, TORUS-LiTE, and PERiLS were quality controlled, including a new wind speed and direction smoothing approach that was developed and applied to the data. An intercomparison dataset was also created by launching Windsonds and Vaisala radiosondes in convective environments using a single balloon setup in different cloud conditions. Findings from the intercomparison analysis showed that the Windsonds have a warm bias that increases with height due to a lack of solar radiation correction and a slow relative humidity response time. In addition, Vaisala wind correction may overcorrect the wind speeds near the surface. Overall, it was shown that Windsonds can be used confidently as low-level in situ observations within convective environments, but has but has less confidence at higher altitudes and in conditions outside of convection. This project resulted in five datasets published, two conference presentations, one paper about to be submitted, and support of one GRA.

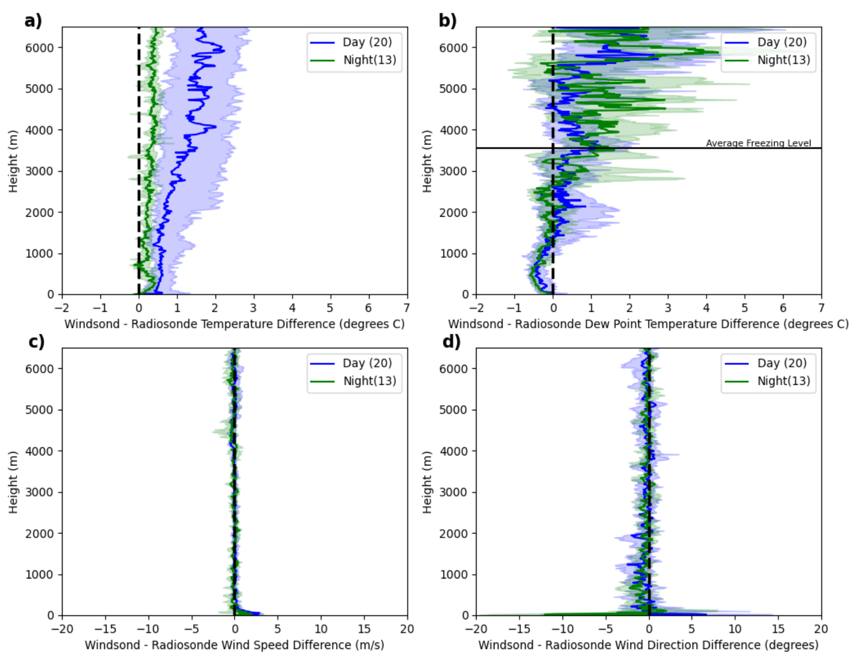


Figure 2-102: Variable difference between Windsond S1H2 and Vaisala RS41-SGP for a) temperature in degrees Celsius, b) dew point temperature in degrees Celsius, c) wind speed in m/s, and d) wind direction in degrees. The median temperature difference for the day (night) flights is plotted as the blue (green) line for each variable with the interquartile range shaded in blue (green).

CIWRO Themes: Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Lauren Pounds, Rachel Miller, Andrew Wade
Project Title: Comparing observed tornadic and non-tornadic environments from multiple field campaigns in the Southeast US
Relevance to NOAA: This project supports the NOAA mission by developing a database of Southeast US tornadic environments to be used by partners in understanding an environment's tornadic and severe potential in the Southeast US.

The goal of this project is to create a database of severe weather environments in the Southeast US. The database is created using available observed atmospheric soundings from 8 years of Southeast US field campaigns including VORTEX-SE, meso18-19, and PERiLS. From the three campaigns, 40 relevant cases with thousands of soundings in total have been identified. We generate composite soundings to evaluate the difference between environments producing different storm modes as well as tornadic vs. non-tornadic environments. Continuous collaboration with forecasters from the SPC is ongoing to visualize our composite soundings in their operational systems and use them as a reference tool to aid in their forecasting efforts. This ongoing work has resulted in one conference presentation and another planned for early 2025 and at least one journal article is currently being written.

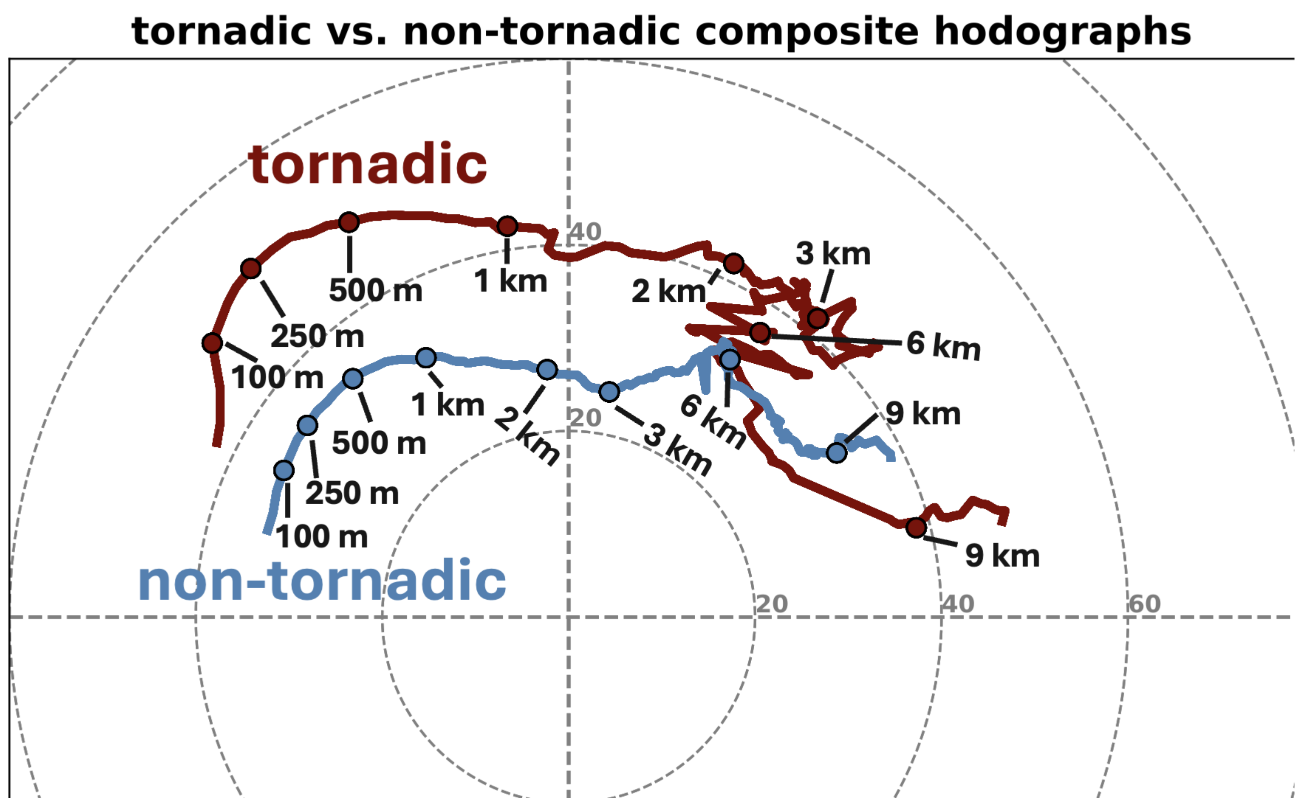


Figure 2-103: Composite tornadic (red) and non-tornadic (blue) composite hodograph (values in kts). The circles along the hodograph indicate different levels of interest.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributor: Morgan Schneider
Project Title: Rapid-scan radar observations of a QLCS mesovortex during PERiLS 2023
Relevance to NOAA: This project supports the NOAA mission by using radar and surface observations from a VORTEX-USA-funded field project to better understand rotation in squall lines and improve predictability of tornadic and non-tornadic squall lines.

During March and April 2023, OU Rapid X-band Polarimetric (RaXPol) mobile radar deployed in support of the Propagation, Evolution, and Rotation in Linear Storms (PERiLS) field campaign to collect targeted observations of squall lines and mesovortices in coordination with other observing platforms. On 3 March 2023, RaXPol collected close-range rapid-scan observations of a non-tornadic mesovortex in a severe squall line near Stuttgart, Arkansas, with NSSL mobile mesonets performing coordinated transects ahead of and behind the mesovortex. During the observing period, a microscale vortex and low-level rotor developed within the larger mesovortex and remained within 10 km of RaXPol's location for several minutes, allowing very low-level observations of the development and evolution of a transient non-tornadic vortex feature to be collected at high spatial and temporal resolution. RaXPol single-Doppler observations are analyzed with surface measurements from the mobile mesonets to relate low-level radar observations of the evolution of the non-tornadic mesovortex to corresponding near-surface kinematic and thermodynamic characteristics of the environment and cold pool. This project is ongoing and has resulted in two conference presentations, with one journal paper currently being planned.

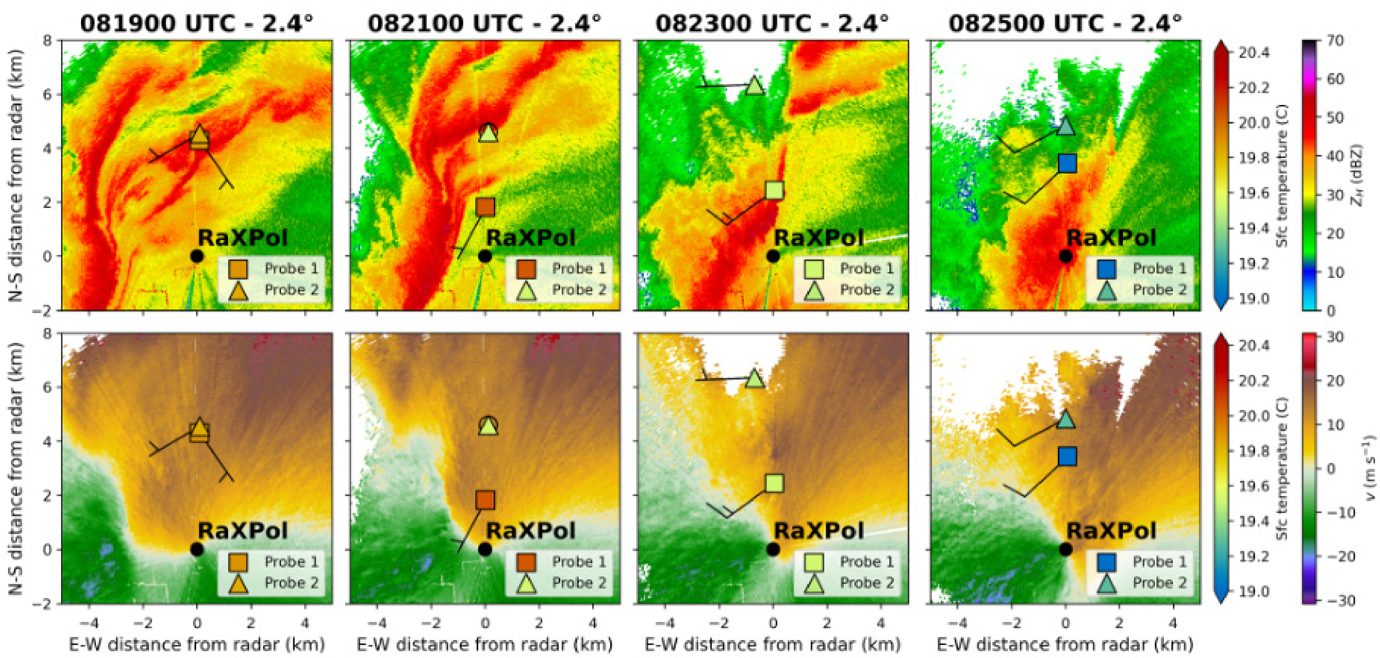


Figure 2-104: Radar reflectivity and radial velocity at a 2.4° elevation angle as the mesovortex and small-scale vortex pass within close range of RaXPol. The positions of the NSSL mobile mesonets are overlaid, with wind barbs showing the observed surface wind speeds (in m/s) and the color of the position markers indicating the observed air temperatures.

CIWRO Themes: Weather Radar and Observations, Mesoscale and Stormscale Modeling
CIWRO Contributor: Dominic Candela
Project Title: Understanding the influence of land cover transitions on tornadoes through high resolution simulations and damage analysis from uncrewed aircraft systems
Relevance to NOAA: This project supports the NOAA mission by utilizing observation instruments and numerical simulation to better understand tornado behavior.

The goal of this project is to better understand the interaction between tornadoes and heterogeneous land cover. This study utilizes Cloud Model 1 (CM1) to perform high resolution numerical simulations of a tornado translating over various surface roughness distributions. The simulations are inspired by unique damage instances captured by the NSSL-CIWRO damage assessment team from the Rolling Fork, MS tornado. The simulations particularly focus on an instance where the tornado progressed through an isolated patch of trees. As the tornado exited the patch of trees a northern shift and widening of the path occurred (Figure a). Simulation results have shown a change in structure of the vortex as it progresses over the higher surface roughness area with a more disorganized inner core and a decrease in aerial extent of the highest velocity (Figure b). The simulations have not shown a significant shift in the path upon exit, but a widening of the maximum winds and treefall was found. This ongoing project has resulted in 1 conference presentation and is in collaboration with David Bodine (SoM/ARRC).

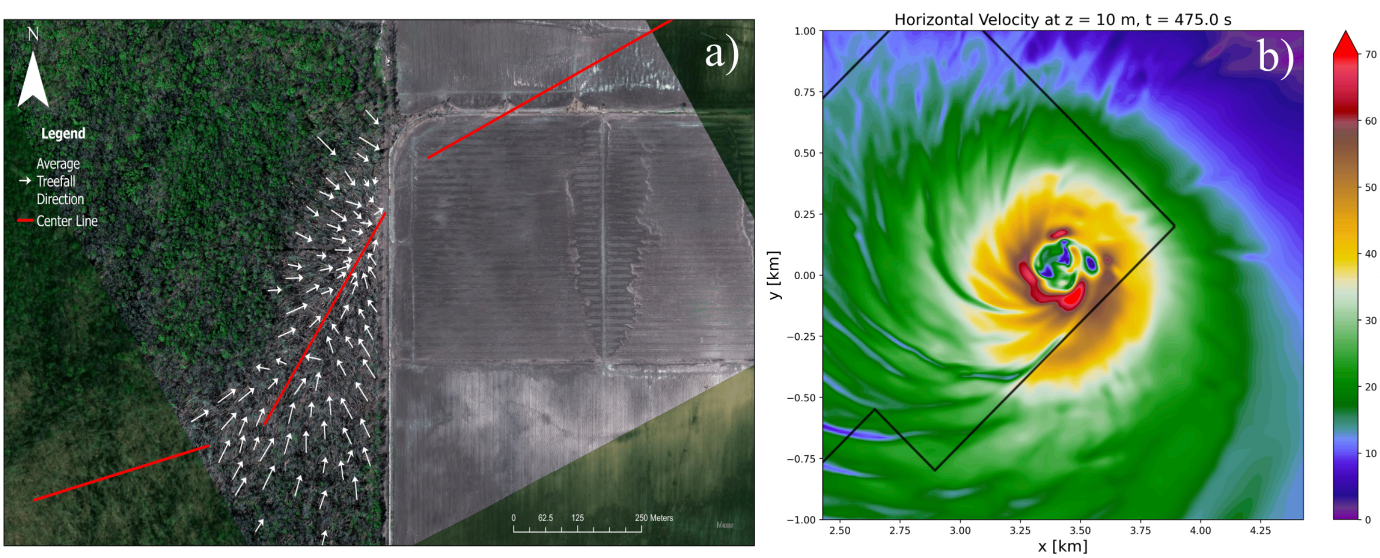


Figure 2-105: Path of the Rolling Fork tornado captured from UAS as it exited a patch of trees (a). Horizontal velocity in the simulation as the tornado is about to exit the higher surface roughness (b). Black contour lines indicate the surface roughness distribution.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributor: Petar Bukovcic
Project Title: Data acquisition, maintenance, and calibration of various weather instruments at Kessler's farm (KAEFS)
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds and improving observation quality and/or stewardship

We installed, and managed (maintenance, calibration, data acquisition/processing, etc.) thirteen meteorological instruments at the Kessler Atmospheric and Ecological Field Station (KAEFS; OU test site ~ 30 km south-southwest of NWC, near Purcell, OK), in the period from 2006 until present. The instruments at the KAEFS are the following: 2D Video Disdrometer (2DVD; 2nd gen.), OTT Pluvio2 L 400, FD70 forward scatter sensor, two orthogonally set OTT Parsivel2 disdrometers, Micro-Rain Radar (MRR), heated tipping bucket (HTB), two temperature, humidity, pressure, and wind sensors (see the image). The instrumented site is in a small, naturally shielded valley, located about 400 m from Oklahoma Mesonet (Washington) station. All sensors are calibrated two times per year, or more frequently if needed. The instruments are utilized for verification of the remote estimates of precipitation with in situ measurements below the radar (KTLX, KOUN, KCRI, ATD, etc.) beam. The data are provided in a user-friendly format to interested parties and collaborates with projects needing the data. For example, NASA used Kessler's farm data in 2021 for GPM validation. Tangible outcome: 3 formal journal articles, 7 conference presentations.

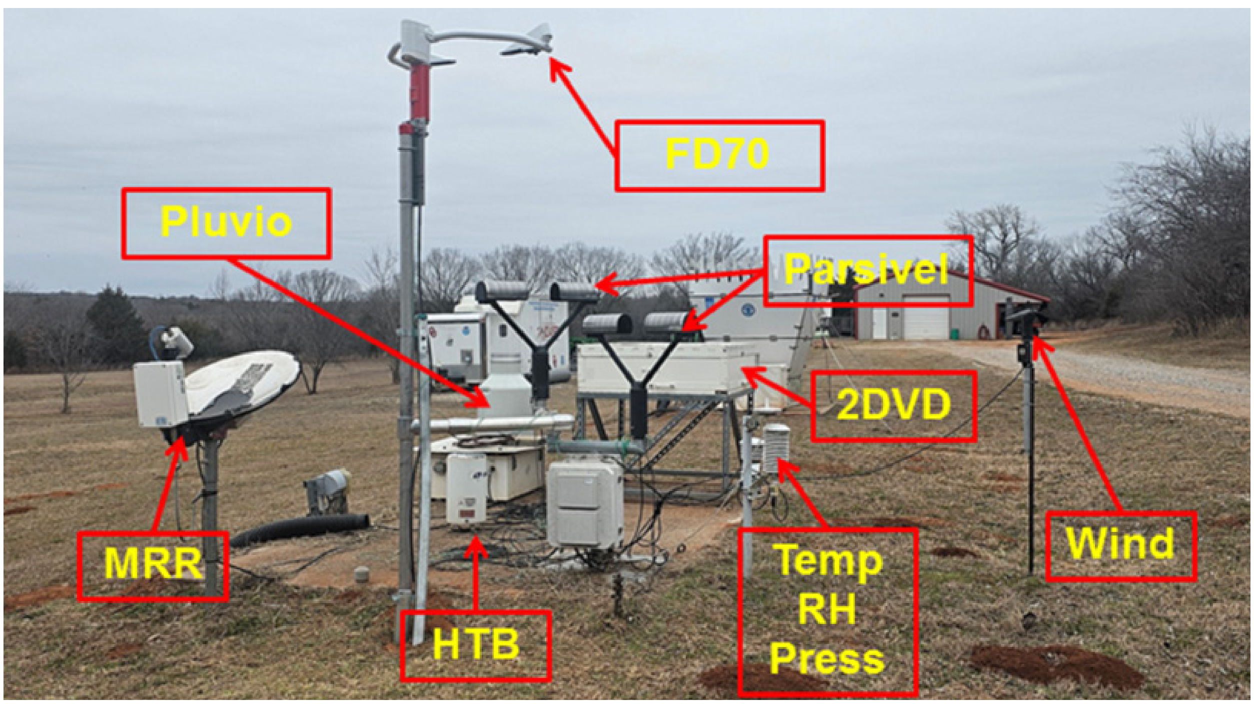


Photo 2-5: KAEFS instruments: Micro rain radar (MRR), FD70 forward scatter sensor (extinction/visibility), 2D video disdrometer (2DVD), two Parsivel2 laser disdrometers, Pluvio L 400 weighing gauge, heated tipping bucket (HTB), two temperature, relative humidity, pressure, and wind sensors

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Cesar Salazar Aquino, Alexander Ryzhkov
Project Title: Estimation of relative humidity and cloud water content from the induced phase change in electromagnetic waves
Relevance to NOAA: This project supports the NOAA mission by developing next-generation observational capabilities.

This project proposes an algorithm to estimate the Relative Humidity (RH) from the change in signal phase along the path of electromagnetic waves transmitted by an instrument and received by cellphones. It is expected that the estimations provided will be statistically adequate and require minimal additional infrastructure. Estimations of RH will be based on different parameters measured in a propagation path, such as, but not limited to, the carrier frequency of the waveform passing through the path, the differential phase induced on that waveform by the RH across that path, the average temperature in such path, the length of the path, and the time and day of the measurements. The researcher can gather most of those parameters from the MESONET stations. Nevertheless, the differential phase will be measured from an instrument assigned to this project, specifically designed for this function. Current experiments are designed as a first approximation and test of concept. Therefore, although the project aims to estimate the RH from cellphones, the instrument currently assigned to this project operates at a frequency, and transmits a waveform, different from the one used on cellphones.

Photo 2-6: Experimental setup designed to gather measurements of differential phase on propagation paths of different lengths (within the specifications of the instrument). The instrument consists of two boxes, one transmitter and one receiver. An electromagnetic wave is transmitted/received through horn antennas, and a copy of that signal is transmitted/received through an optical cable. Then, both signals are "mixed," on the receiver to calculate the differential phase. The calculated differential phase is expected to correspond to the change induced by the RH that affected the signal transmitted/received by the horn antennas, which is not present on the signal transmitted/received via the optical cable.

CIWRO Themes: Weather Radar and Observations, Mesoscale and Stormscale Modeling
CIWRO Contributors: Yongjie Huang, Greg McFarquhar, Alexander Ryzhkov
Project Title: Microphysical processes producing high ice water contents (HIWCs) in tropical convective clouds
Relevance to NOAA: This project supports the NOAA mission by advancing our understanding of cloud microphysical processes in convective clouds, and by improving the representation of clouds in numerical models.

Numerous small ice crystals in tropical convective storms are difficult to detect with pilot radars onboard commercial aircraft and can cause aircraft power-loss and damage events. To better understand this phenomenon, airborne in-situ and radar observations from the High Altitude Ice Crystals – High Ice Water Content (HAIC-HIWC) field campaign were combined with high-resolution numerical simulations to assess biases in model representations and investigate the underlying cloud microphysical processes responsible for the formation of these ice crystals. Results revealed that key processes are either missing or misrepresented in current numerical models, limiting their ability to realistically simulate HIWC regions in tropical storms. To address these deficiencies, two additional secondary ice production (SIP) mechanisms (i.e., fragmentation during ice–ice collisions and fragmentation of freezing droplets) were implemented in the Predicted Particle Properties (P3) microphysics scheme. The updated scheme successfully reproduced HIWC regions across all temperature levels, demonstrating remarkable agreement with observations. This work has led to the publication of 2 peer-reviewed journal papers.

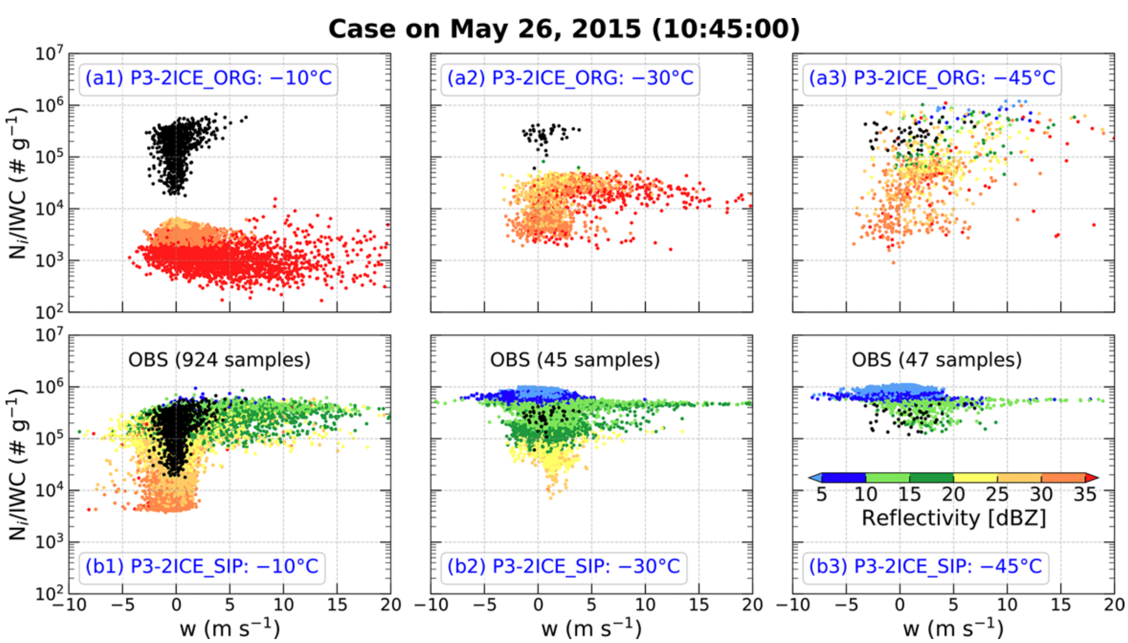


Figure 2-106: Scatter plots of (black) observed and (colorized) WRF simulated ice number concentration (N_i) divided by ice water content (IWC) as a function of vertical velocity (w) in regions with IWC > 1 g m^{-3} at temperatures of (a1, b1) −10 °C, (a2, b2) −30 °C, and (a3, b3) −45 °C. The WRF simulation using the original P3 scheme is shown in (a1)–(a3), and the WRF simulation using the updated P3 scheme is shown in (b1)–(b3). The scatter plots of WRF simulations are color-coded according to the magnitude of radar equivalent reflectivity factor (dBZ).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Yongjie Huang, Dhwanit Mise, Greg McFarquhar, Alexander Ryzhkov, Saurabh Patil, Andrew Dzambo
Project Title: Dependence of convective cloud microphysical properties and convective cell properties on meteorological and aerosol conditions
Relevance to NOAA: This project supports the NOAA mission by advancing our understanding of convective clouds in coastal cities.

Convective clouds play a vital role in Earth's energy balance and water cycle, yet their sensitivity to meteorological and aerosol conditions, combined with limited observational constraints in parameterizations, introduces significant uncertainties in weather models. This project investigates the impact of meteorological and aerosol conditions on convective cloud microphysics and cell properties using data from the TRACER and ESCAPE field campaigns, machine learning techniques, and numerical simulations with a super-droplet microphysics scheme. A random forest model identifies vertical velocity, temperature, and aerosol optical depth as key factors influencing cloud water content and droplet size distributions, with observed trends successfully reproduced by parcel model simulations. Radar observations of over 400 convective cells reveal that long-lived cells are deeper, broader, and have higher reflectivity, with key predictors for cell lifetime including precipitable water vapor, lapse rate, wind shear, and aerosol loading. The study also highlights the role of aerosols in influencing convective intensity, with intermediate aerosol loading favoring higher reflectivity at mid-levels, while short- and long-lived cells exhibit distinct aerosol composition characteristics. The findings provide critical observational constraints for improving cloud parameterizations in weather models, with results disseminated through 2 manuscripts and 3 conference presentations with the involvement of 2 GRAs. Large-eddy simulations are currently underway to investigate the underlying mechanisms governing these observed dependencies.

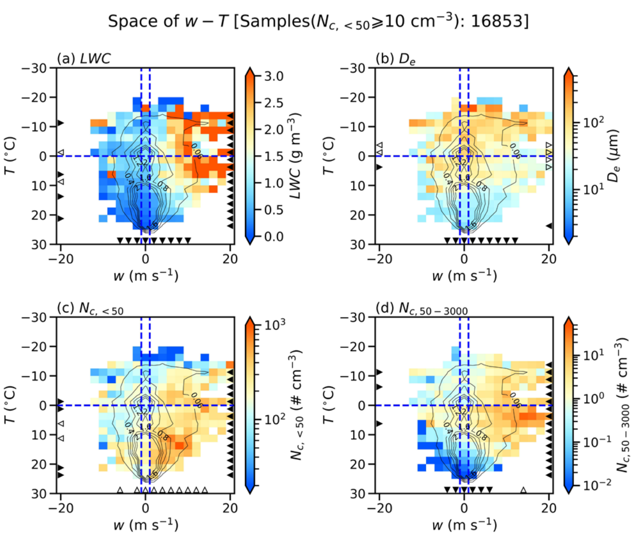


Figure 2-107: Variation of cloud properties (a) cloud water content, (b) droplet effective diameter, number concentration for (c) Dmax < 50 □m, and for (d) 50 □m < Dmax < 3000 □m in the vertical velocity (w)-temperature (Temp) parameter space.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Jonathan Douglas, Greg McFarquhar
Project Title: Characterizing variations of cloud microphysical properties with respect to position in snowbands and small-scale vertical motion: A case study of 23 January 2023 storm during IMPACTS
Relevance to NOAA: This project supports the NOAA mission by improving the knowledge of microphysical properties and processes occurring in winter storms, which can be used to improve numerical weather models.

The NASA Investigation of Microphysics and Precipitation for Atlantic Coast Threatening Snowstorms (IMPACTS) project studied cloud microphysics in extratropical cyclones from 2020 to 2023 using two aircraft: a P-3 for in-situ particle data and an ER-2 for remote sensing. A standout case was the 23 January 2023 winter storm, which featured a long-lived, stationary snowband thoroughly sampled by both aircraft. Flight legs parallel and perpendicular to the snowband provided insights into storm structure and microphysics. This study examined how cloud properties—such as particle concentration, liquid water content, median mass diameter, and cloud phase—varied with storm features. A cloud phase identification algorithm was developed to link cloud properties to rapidly changing features like updrafts and downdrafts, identified using P-3 in-situ probes. Results showed larger liquid water droplets and higher ice particle concentrations in updrafts, while downdrafts contained smaller particles and more liquid water than surrounding areas. The snowband region had a higher median mass diameter, suggesting larger or more numerous particles. Additionally, cloud particle diameter increased with height below cloud top (HBCT), indicating growth during descent, while liquid water was most prevalent near cloud top, where particle formation occurs. This research has led to three conference presentations and an upcoming manuscript submission.

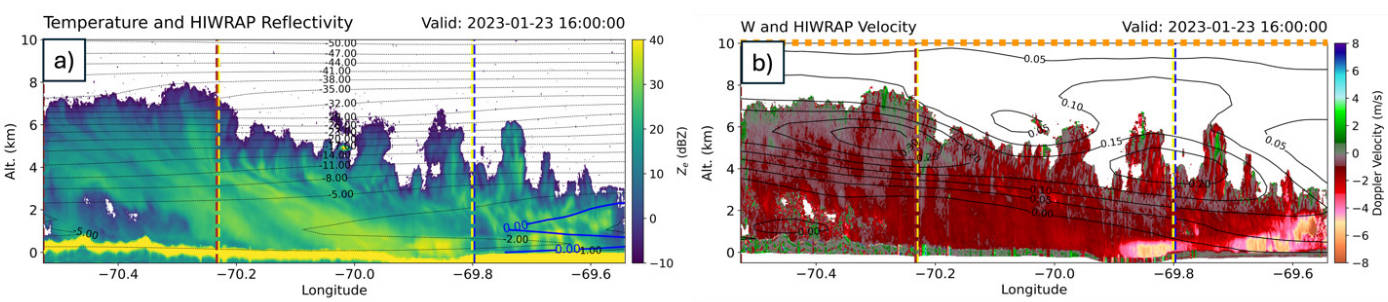


Figure 2-108: a) HIWRAP Reflectivity cross section of snowband with RAP temperature contours. b) HIWRAP vertical velocity of snowbands with RAP vertical motion contours for every 0.05 m s^{-}.^{1}

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Saurabh Patil, Greg McFarquhar, Yongjie Huang
Project Title: Observed relationships between aerosol, meteorological, dynamical and cloud microphysical properties during ESCAPE
Relevance to NOAA: This project improves NOAA's understanding of aerosol impacts on convective storms, aiding weather prediction and hazard assessment in coastal regions.

The area around Houston, Texas represents an ideal natural laboratory for studying relationships between aerosols, environmental conditions, and cloud microphysical and dynamical properties because isolated convective cells frequently occur under the influence of the sea breeze flow with limited synoptic scale influences. Further, there are large contrasts and interfaces in aerosol conditions and surface characteristics (land vs. ocean). The National Research Council of Canada Convair-580 and Stratton Park Engineering Company's Learjet aircraft together sampled about 280 intense convective cloud core segments in different meteorological regimes along the coast of Texas and Louisiana between 31 May and 17 June 2022. The statistics of altitude-sorted updraft core segments show larger derived quasi-steady state supersaturations (S_{QSS}) and stronger updrafts with increased height above the cloud base. The mean S_{QSS} was approximately 0.4%, but a case of an isolated thunderstorm ingesting clean maritime air showed a peak S_{QSS} of nearly 11% collocated with extreme updrafts reaching up to 21 m s^{-1} in the mixed-phase region of the storm. This indicates the potential for condensational invigoration. Examination of other cases did find the occasional occurrence of S_{QSS} larger than 4%, but these conditions were quite rare. Based on the observations which include airborne X-band radar, conditions where large S_{QSS} might be expected are inferred. Additionally, the airborne in-situ observations below cloud are used to classify convective cores into three aerosol regimes: pristine, intermediate, and polluted. After meteorologically constraining these regimes using CAPE, a higher probability of stronger updrafts in intermediate and polluted conditions, and higher probability of larger than mean S_{QSS} in clean and intermediate conditions is found. Although these results are consistent with the condensational invigoration hypothesis, they are subject to the quasi-steady state assumption. This work has resulted in 4 conference presentations and one outstanding student presentation award at the AGU2023 meeting.

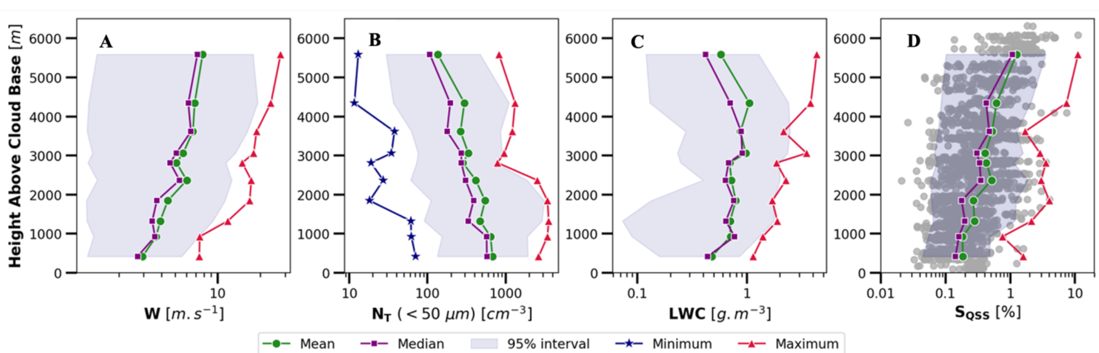


Figure 2-109: Figure shows the variation of updrafts (A), Cloud droplet number concentrations (B), Liquid Water Content (C) and S_{QSS} (D) statistics with height above cloud base.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Erika Pruitt, Greg McFarquhar, Heather Reeves
Project Title: Enhancing weather observations: bridging the gap between airborne measurements and ASOS data
Relevance to NOAA: This project supports the NOAA mission by improving weather predictions and providing this knowledge and information with others.

Automated Surface Observing System (ASOS) stations are widely distributed across the United States, providing local current weather conditions like temperature and precipitation. The data received supports aviation operations, local forecasting offices and many meteorological research communities at universities, federal laboratories and private companies. Despite their many capabilities, there are challenges in accurately capturing spatial variability with them, and thus variation in cloud and precipitation is missed by them. This research compares airborne data collected during the NASA Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) field campaign with the ground based ASOS observations to assess the representativeness of the ASOS data. Vertical profiles of radar reflectivity from the Ka-band High Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) along the ER-2 flight tracks for all flights conducted in 2020, 2022, and 2023 are generated and compared to the ASOS data. The comparison of the HIWRAP data and the ASOS data determines the consistency between the upper-level precipitation pattern and the measured intensity at the ground. The findings so far revealed that the ASOS stations do not capture variability shown by the HIWRAP, especially for times that the ASOS measures higher precipitation. Furthermore, in cases where the ASOS station observes lower precipitation intensities, inconsistencies are found between the radar reflectivity and the ASOS station readings. This research has been presented in two conference presentations.

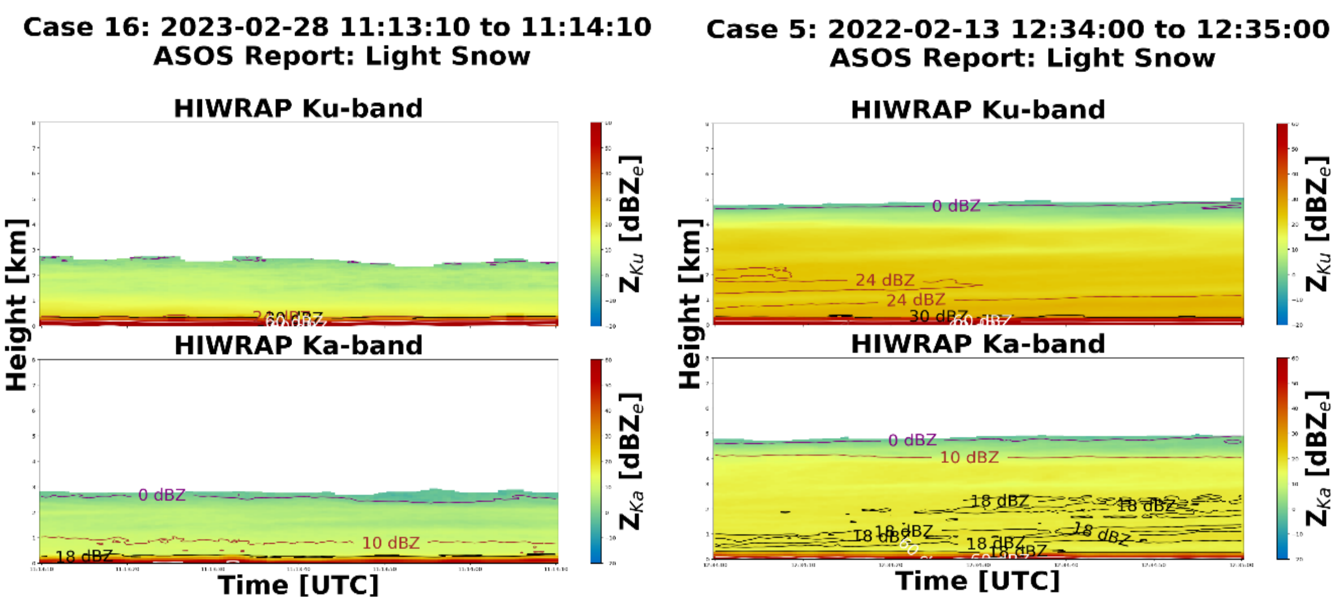


Figure 2-110: Case 16 represents the lowest Ku and Ka-band reflectivity average when ASOS reported light snow. Case 5, same as Case 16 except represents the highest average.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Dhwanit Mise, Yongjie Huang, Greg McFarquhar, Alexander Ryzhkov
Project Title: dependence of convective cell properties on meteorological and aerosol conditions during TRACER
Relevance to NOAA: This project supports the NOAA mission by advancing our understanding of deep convection near coastal cities.

The Tracking Aerosol Convection Interactions Experiment (TRACER) campaign (2021–2022) in Houston observed convective cell evolution under diverse environmental conditions using the C-Band Scanning ARM Precipitation Radar (CSAPR2) and other instruments. This study focuses on convective cell properties during the TRACER Intensive Operational Period (IOP) (June–September 2022) using a convective cell tracking dataset. Preliminary findings from this work indicate that long-lived convective cells are broader and deeper, with an average width of ~6.63 km and height of ~9.86 km, compared to shorter-lived cells, which average ~3.43 km in width and ~6.43 km in height. A Random Forest model identifies precipitable water vapor (PWV), 2–6 km lapse rate, 0–8 km wind shear, and aerosol optical depth (AOD) as key factors influencing cell lifetime. In cleaner environments (AOD < 33rd percentile), PWV significantly enhances cell lifetime (Fig. c), while in higher AOD environments this variation is not uniform. AOD also impacts cell height, width and radar reflectivity (Z), with intermediate AOD levels (33–66th percentile) favoring increased Z at 4–8 km height. Short-lived cells are associated with higher aerosol concentrations at the size ranges of 10–100 nm and 500–1000 nm, whereas long-lived cells are linked to more organic and sulfate aerosols. In contrast, short-lived cells have higher black carbon concentration. This work has been presented in 1 conference presentation.

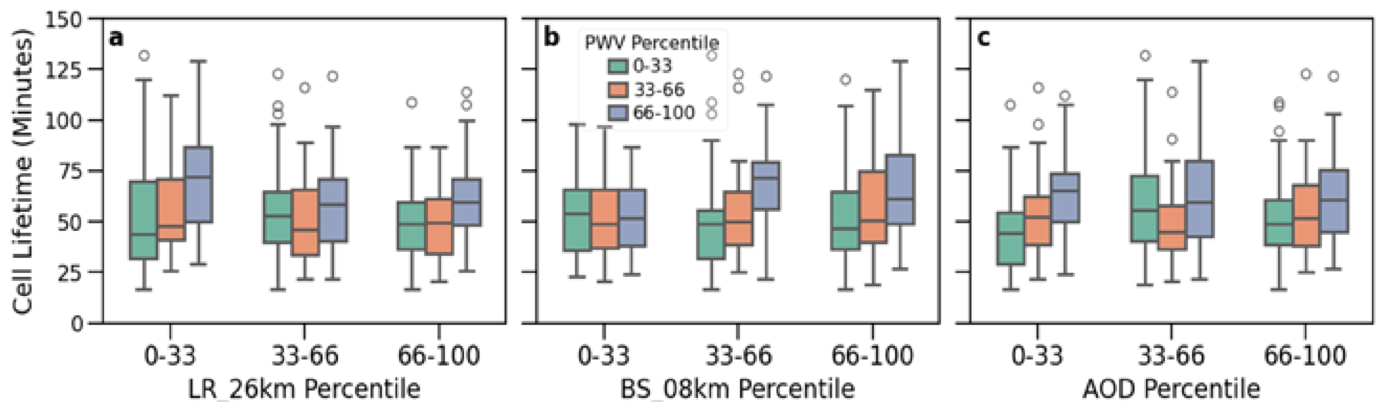


Figure 2-111: Boxplots showing cell lifetime (in minutes) as a function of different variables, stratified by PWV Percentiles (0–33, 33–66, 66–100). (a) Cell Lifetime by PWV and LR_26km. (b) Cell Lifetime by PWV and 08km_shear (c) Cell Lifetime by PWV and AOD.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Greg McFarquhar, Zeqian Xia
Project Title: Dependence of boundary layer cloud properties on environmental conditions and geographic locations during cold air outbreaks - Results from CAESAR, COMBLE, CAPE-k, and MARCUS
Relevance to NOAA: Understanding of Cold Air Outbreaks is important for NOAA as cold air outbreaks can have impact on continental United States

Accurate representation of Cold Air Outbreaks (CAOs) and affiliated marine boundary layer (BL) clouds in models is challenging. There is a compelling need to determine how BL clouds properties and formation mechanisms vary with surface, geographic, environmental and aerosol conditions during CAOs. Here the properties of polar BL clouds over the North Atlantic (NA) and Southern Ocean (SO) are compared using observations from the 2019-20 Cold-air Outbreaks in the Marine Boundary Layer Experiment (COMBLE) conducted over the NA, the 2017-18 Measurements of Aerosols Radiation and CloUds over the Southern ocean (MARCUS) campaign, the 2024 Cold Air outbreak Experiment in the Sub-Arctic Region (CAESAR) field campaign, and the 2024-25 Cloud And Precipitation Experiment at kennaook (CAPE-k). Results from the NA and SO show that the characteristics of BL clouds during CAOs depend on location even when the environmental conditions are consistent between regions. This suggests more field campaigns in varied conditions are necessary to better identify how cloud properties depend on environmental conditions in order to provide further insight into the processes that affect cloud evolution. These results provide key insights towards improving the representation of boundary layer clouds during cold air outbreaks in weather models. Outcomes include one refereed manuscript and 5 conference presentations.

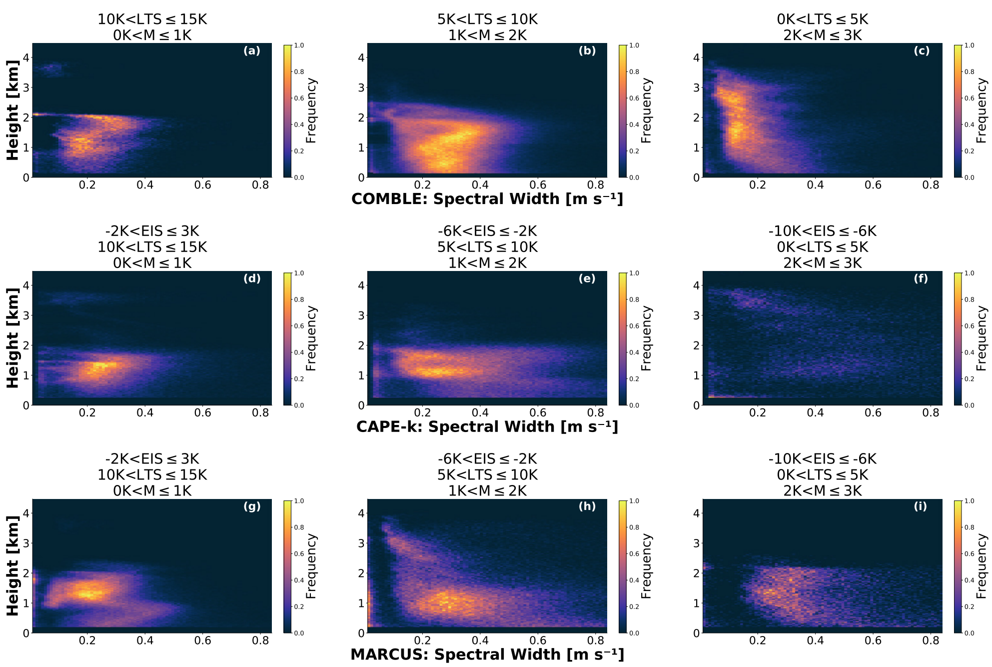


Figure 2-112: Vertical distribution of radar spectral width for COMBLE (upper panel; Ka-band), CAPE-k (middle panel; Ka-band), and MARCUS (bottom panel; W-band) across different ranges of CAO intensity (M), Lower Tropospheric Stability (LTS), and Estimated Inversion Strength (EIS).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Nick Amundsen, Greg McFarquhar
Project Title: Quantifying the dependence of cloud vertical structure during cold air outbreaks on environmental conditions - Results from CAESAR
Relevance to NOAA: Understanding of cold air outbreaks is important because they can have major impacts on the continental United States.

Cold-air outbreaks (CAOs) have an overwhelming influence on global atmospheric and oceanic circulations, yet their cloud regimes remain poorly sampled and are therefore not fully understood nor well-represented in weather models. To bridge this gap, the Cold-Air outbreak Experiment in the Sub-Arctic Region (CAESAR) field campaign collected airborne in-situ and remote sensing data from the National Science Foundation (NSF) / National Center for Atmospheric Research (NCAR) C-130 aircraft based in Kiruna, Sweden from February 22 to April 7, 2024. During the campaign, the structure of marine boundary layer clouds during CAOs was investigated, and questions about coupled atmosphere-ocean-ice processes were addressed. This work compiles and analyzes 58 vertical profiles within cloud over eight full-fetch research flights. In-situ cloud probe data reveals that there is large variability in the measured cloud properties, requiring further investigation into the factors driving this variability. To address this, vertical profiles are stratified based on various meteorological and environmental conditions. Preliminary findings suggest that there is no clear monotonic variation in average vertical profiles categorized by cloud base temperature and sea surface temperature. However, many other environmental conditions such as cloud type, vertical velocity, estimated inversion strength, lower tropospheric stability, aerosol concentration, and surface flux will be investigated in the future. Thus far, this work has resulted in two conference presentations and one poster.

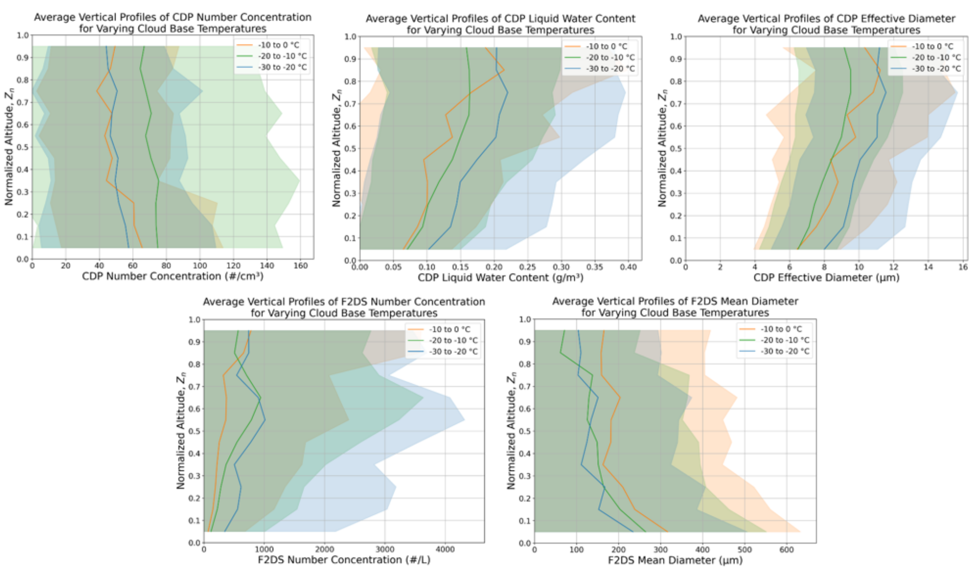


Figure 2-113: Average vertical profiles of common cloud microphysical properties derived from the CDP and F2DS cloud probes as a function of normalized altitude (0 is cloud base & 1 is cloud top). Each color represents the average profile where the cloud base temperatures were between -30 to -20°C (blue), -20 to -10°C (green), and -10 to 0°C (orange).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Amanda Richter, Greg McFarquhar
Project Title: Identification and characterization of primary ice environments in convection observed by the ESCAPE field campaign
Relevance to NOAA: This project supports the NOAA mission by advancing our understanding of the conditions surrounding primary ice formation in convection, which will improve research and predictive modeling capabilities.

Clouds containing ice-phase particles are responsible for the vast majority of rainfall across the Earth's surface. Despite this, ice-phase processes are often poorly represented in convective-scale models. Primary ice is especially difficult to study due to low ice particle concentrations at the time of primary ice formation, and the rate at which secondary ice multiplication dominates cloud glaciation. This work is using in-situ airborne measurements from the NCAR Experiment of Sea Breeze Convection, Aerosols, Precipitation, and Environment (ESCAPE) field campaign to detect instances of first ice with the intent of investigating cloud and environmental properties at the time of primary ice formation. Multiple cases with probable primary ice have been identified. Work is ongoing to categorize environments with first ice, secondary ice, and no ice. Convective clouds in each of these categories are being assessed to determine cloud properties such as vertical velocity, top temperature, base temperature, top and base altitude, particle size distribution, and age to improve our understanding of cloud characteristics before, during, and after the formation of primary ice. The outcomes from this work are 2 conference presentations.

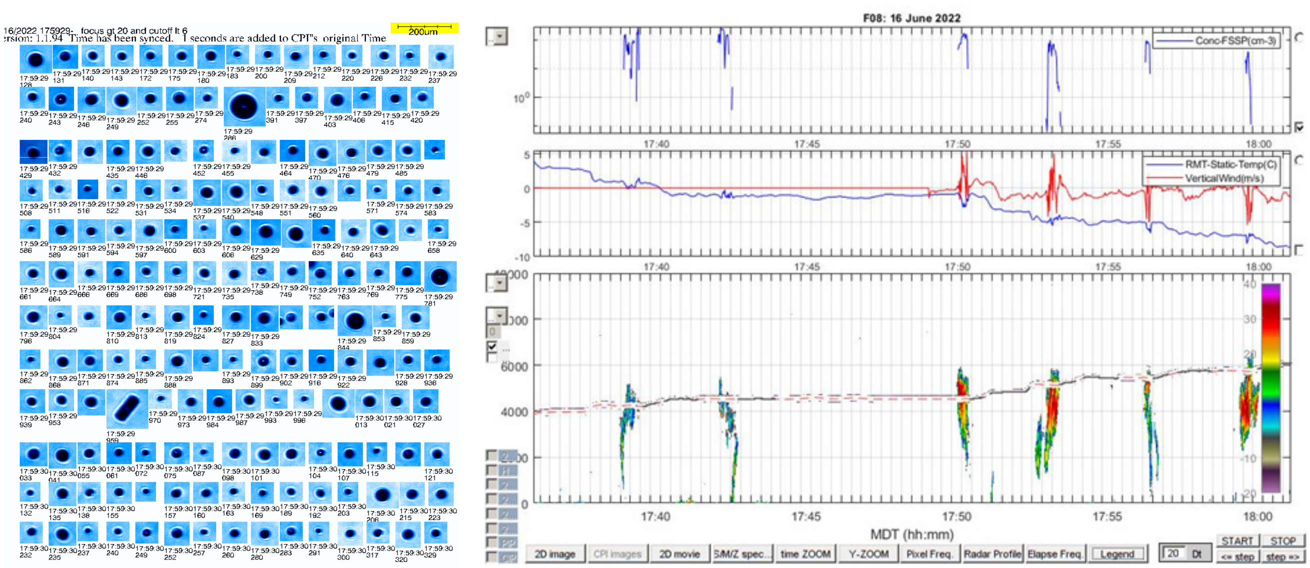


Figure 2-114: In-situ Hawkeye-CPI Cloud Particle Images containing low ice particle concentrations surrounded by liquid water droplets during a cloud penetration on June 16, 2022 at 17:59 UTC, which is evidence of a primary ice environment (left). Particle concentration (top), ambient temperature and vertical wind (middle), and Ka-band reflectivity (bottom), with the cell in question outlined (right).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Mastooreh Ameri, Greg McFarquhar
Project Title: Addressing uncertainties in cloud microphysical measurements - Evaluating optical array probe data processing techniques
Relevance to NOAA: This project supports the NOAA mission by advancing our understanding cloud microphysical measurement techniques

Accurate cloud microphysical measurements are crucial for understanding atmospheric processes, yet uncertainties arise from variations in data processing techniques used for airborne cloud probes. This project evaluates these uncertainties by comparing microphysical properties derived from optical array probe (OAP) data processed with different algorithms. By analyzing discrepancies in particle size distributions, detection counts, and derived properties, the study assesses the impact of various processing techniques. The findings will enhance measurement accuracy, reduce inconsistencies across research groups, and improve comparisons of cloud properties under different environmental conditions. The research focuses on algorithms used for the SPEC 2D-S, SPEC HVPS-3, DMT CAPS-CIP, and DMT PIP, highlighting how differences in out-of-focus particle corrections, shattered fragments, and sample volume calculations affect final measurements. To systematically assess these variations, synthetic datasets were processed by multiple international research groups using their own algorithms. This collaboration includes OU, NCAR, DLR, ECCC, the University of Wyoming, NRC, SPEC Inc., the University of Leeds, and the University of Clermont Auvergne. Outcomes include two conference presentations.

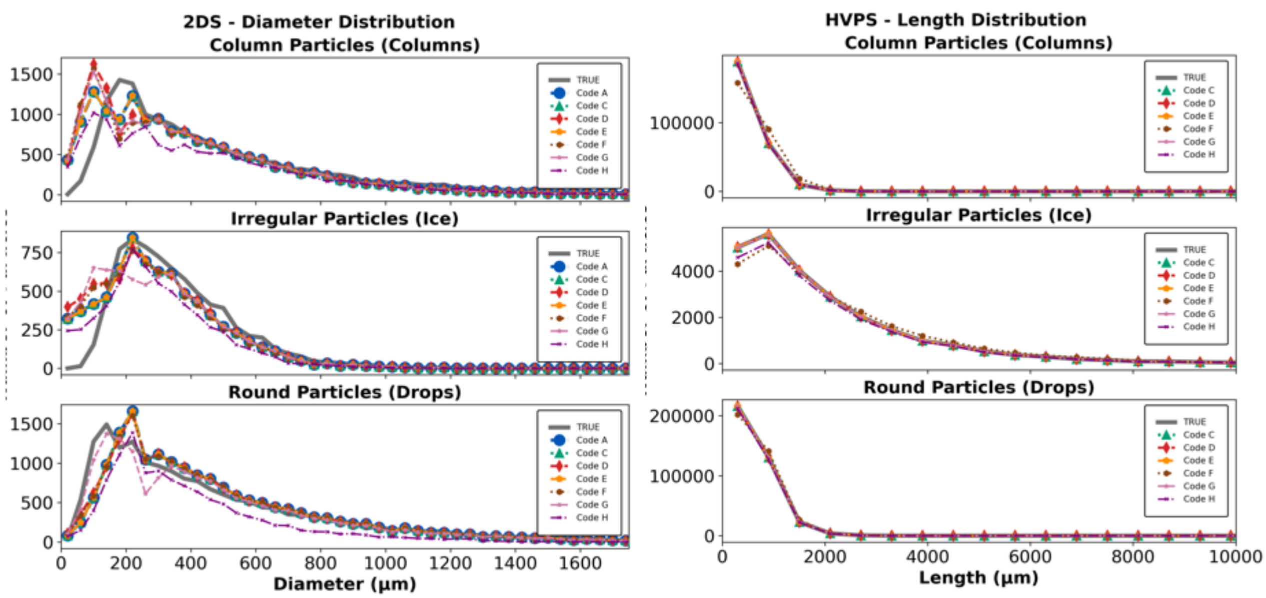


Figure 2-115: (left) Diameter distribution of cloud particles measured by the 2D-S optical array probe for three particle habits: columnar ice, irregular ice, and round drops. (right) Length distribution of cloud particles measured by the HVPS optical array probe for columnar, irregular, and round particles.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Peter Brechner, Greg McFarquhar, Yongjie Huang
Project Title: Verifying ice crystal size distributions in winter storms predicted by p3 microphysics using in-situ observations taken during the IMPACTS field campaign
Relevance to NOAA: This project supports the NOAA mission by using in-situ observations of ice crystal size distributions to diagnose problems with the P3 microphysics scheme used in mesoscale storm prediction models.

The Investigation of Microphysics and Precipitation in Atlantic Coast-Threatening Snowstorms (IMPACTS) was conducted in January and February of 2020, 2022, and 2023 to study banding of precipitation in winter storms. Several research flights were conducted during IMPACTS to collect data on temperature, liquid and ice water content, vertical velocity, and particle sizes for different parts of different types of storms. The particle size distributions (PSDs) for ice were fit to a sum of up to three continuous gamma distributions using a multimodal fitting algorithm developed in a previous study, and properties of PSDs were analyzed in relation to environmental conditions such as temperature and storm type. PSDs were found to broaden with temperature, with multimodal PSD likelihood increasing with temperature. No significant dependence on storm type was observed. Observed PSDs for ice were compared to those simulated in the two-moment Predicted Particle Properties (P3) microphysics scheme using 1-category and 2-category ice microphysics. Observed PSDs were found to match those simulated using 1-category ice microphysics most closely, regardless of environmental conditions. Future work will analyze observed and simulated process rates to examine why the PSDs in the 2-category ice microphysics simulations do not match the observed PSDs. This work has resulted in six conference presentations, including one international conference presentation, and one refereed manuscript.

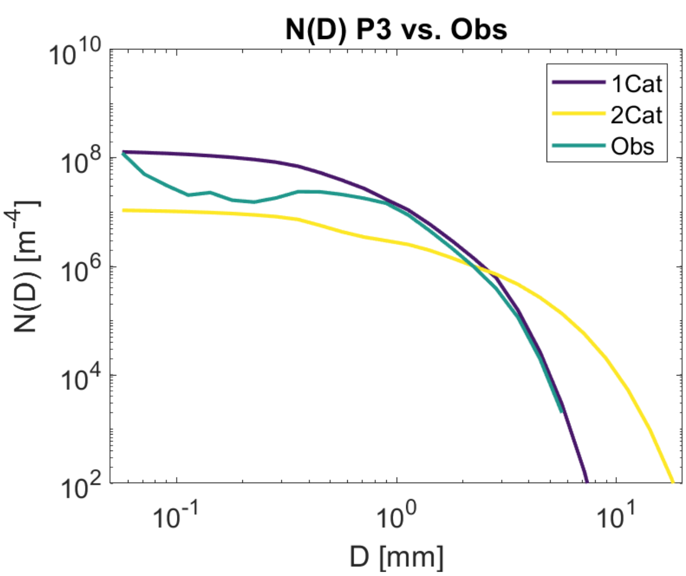


Figure 2-116: Figure shows mean ice crystal size distributions simulated in 1-category P3 microphysics (violet), simulated in 2-category P3 microphysics (yellow), and observed in-situ (turquoise).

CIWRO Themes: Weather Radar and Observations, Mesoscale and Stormscale Modeling
CIWRO Contributors: Alexander Ryzhkov, Jiaxi Hu, Edwin Dunnavan, Greg McFarquhar
Project Title: High concentration of ice: Investigations using polarimetric radar observations combined with in situ measurements and cloud modeling
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds and developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events

This project had the over-arching goal of understanding the reasons for observed size distributions of ice particles in cold clouds. Its approach involves the use of cloud models and field observations by radar and aircraft of real storms. The study was performed by three research organizations: OU, The Hebrew University of Jerusalem, Israel, and Lund University, Sweden. The Israel and Swedish partners were funded by the sub-awards from OU. Cloud modeling studies have been performed by the research teams at The Hebrew University of Jerusalem (HUJ) and Lund University to identify the origins of high concentrations of cloud ice in areas of high ice water content (HIWC). The OU team has developed a methodology for polarimetric radar retrievals of such microphysical parameters of ice. These retrievals have been validated using in situ aircraft measurements during 6 field campaigns and proved to be quite robust and reliable. This allowed to build the first description of the vertical profiles of polarimetric radar variables and retrieved microphysical parameters for the three types of weather systems: continental MCSs, maritime MCSs, and tropical cyclones / hurricanes (Hu and Ryzhkov 2022). The results of the project research are summarized in 13 journal papers.

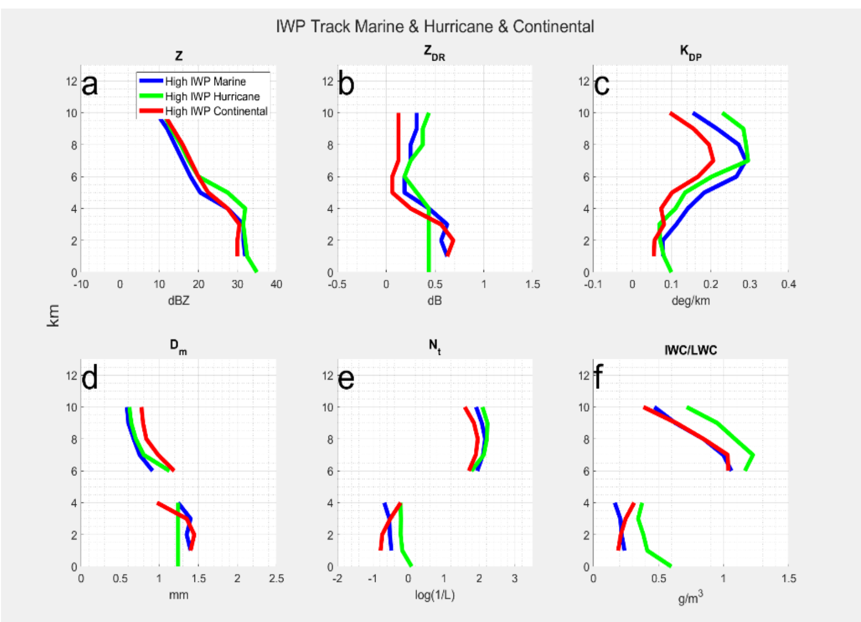


Figure 2-117: Median vertical profiles for the CVP "HIWC" dataset: (a) Z, (b) Z_{DR}, (c) K_{DP}, (d) D_m, (e) N_t, and (f) IWC / LWC. Blue, green, and red lines represent marine, hurricanes, and continental profiles, respectively. From Hu and Ryzhkov (2022).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Alexander Ryzhkov, Petar Bukovcic, Edwin Dunnavan, Greg McFarquhar
Project Title: Studies of the microphysical processes in ice and mixed-phase clouds and precipitation using multiparameter radar observations combined with cloud modeling
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the Radar Next program and/or WSR-88Ds and developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

This NSF project involved theoretical studies, observations with ground-based and airborne in situ microphysical sensors and polarimetric radars, and detailed analysis of the observational data for evaluation of the novel methodologies for radar microphysical retrievals in ice and advanced algorithms for polarimetric snow estimation. This work was done in collaboration with Stony Brook University (PI P. Kollias) and CIRES at the University of Colorado in Boulder (PI S. Matrosov). The methodologies for snow estimation and microphysical retrievals have been developed and evaluated during the IMPACTS and ICICLE field projects using in situ surface and airborne microphysical sensors, a multitude of ground-based operational WSR-88D radars and the research polarimetric radar operating at Ka band (KASPR radar of the Stony Brook University), as well as airborne radars such as X-band / W-band dual-polarization radars owned by the National Research Council of Canada and vertically pointing multi-frequency NASA radars onboard the ER-2 aircraft. All these observations demonstrated good feasibility and efficiency of the suggested methodologies. The results of this research are summarized in 17 journal articles.

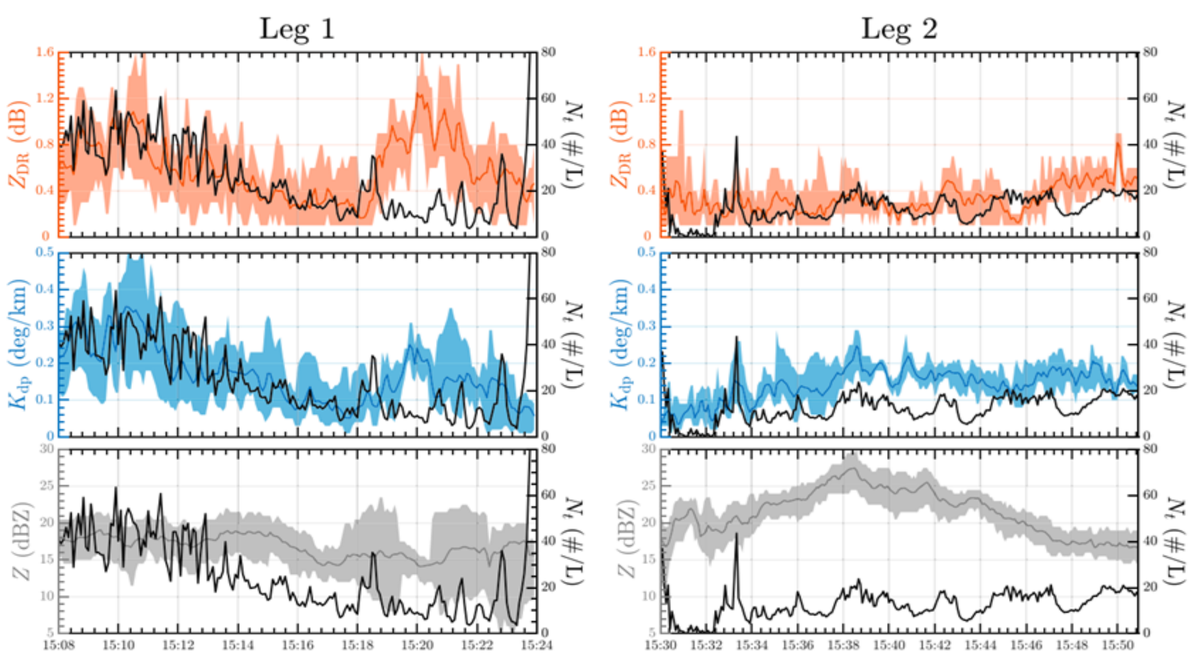


Figure 2-118: IMPACTS observations. Comparison of the total ice concentration N_t measured by the aircraft probe with polarimetric radar variables measured by the WSR-88D radars along Legs 1 and 2 of the P3 aircraft flight on 7 February 2020.

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Edwin Dunnavan, Alexander Ryzhkov
Project Title: Simple analytical expressions for steady-state vapor growth and collision–coalescence particle size distribution parameter profiles
Relevance to NOAA: This project supports the NOAA mission by optimizing platform-agnostic data and information and by enhancing capabilities for the Radar Next program and/or WSR-88Ds.

This project derived a set of theoretical exponential and power-law equations that allows for projecting radar retrievals into regions that are not detected by radar. These equations represent vertical profiles of particle size distribution (PSD) parameters under the steady-state balance of sedimentation, collision-coalesence, and vapor deposition. The equations in this project were evaluated and optimized according to two Lagrangian spiral descents of in situ aircraft measurements in a winter storm and ground-based Parsivel disdrometer measurements. The equations from this work were used to estimate snow aggregation efficiencies and to develop a novel temperature-based aggregation efficiency parameterization representative of synoptic snowstorms (Hu et al. 2024). This project has resulted in 1 conference presentation and 1 journal article (Dunnavan and Ryzhkov 2023).

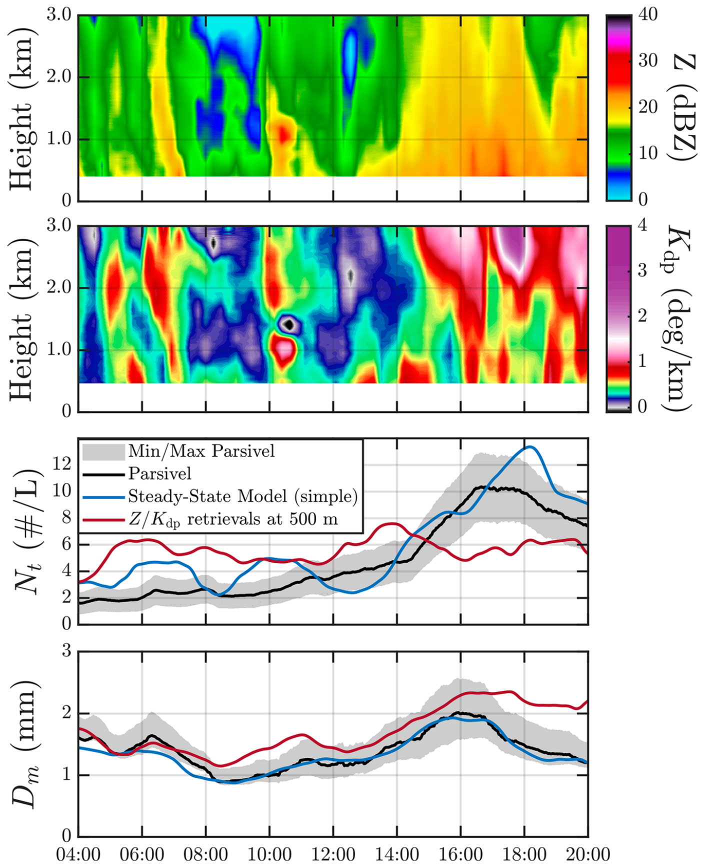


Figure 2-119: Radar retrievals of snow number concentration (Nt) and mean volume diameter (Dm) using reflectivity (Z) and specific differential phase (Kdp) initialized at 3.0 km MSL and projected to the surface (blue lines) outperform the lowest level (500-m) retrievals (red lines) compared to Parsivel ground measurements. From Dunnavan and Ryzhkov (2023).

CIWRO Theme: Weather Radar and Observations
CIWRO Contributors: Christopher Weiss, Isaac Arseneau, Julia Buhrman, Jessica McDonald, Joshua Ostaszewski, Alex Schueth
Project Title: The low-level internal flow of tornadoes (LIFT) experiment at Texas Tech University
Relevance to NOAA: This project supports the NOAA mission by improving weather predictions and improving continuous engagement with partners.

The Low-level Internal Flow of Tornadoes Experiment seeks a better understanding of the near-surface wind fields of tornadoes through radar and in situ observation. Primary objectives include identifying the suitability of extending previously identified models of horizontal tornado structure to the surface, estimating the proper reduction of azimuthal winds from typical operational radar height to the ground, and discovering correlations between radar-based wind speed estimations and observed damage. During the spring of 2024, Texas Tech University and the NSSL had collaborative field data collection on 12 severe storms in the central and southern Great Plains. Over this stretch, observations were made of five tornadoes, including pioneering measurements of the vertical structure close to the surface. Tangible outcomes from this project thus far include one conference presentation. Two graduate research assistants are being supported, and we are partnering with NSSL.

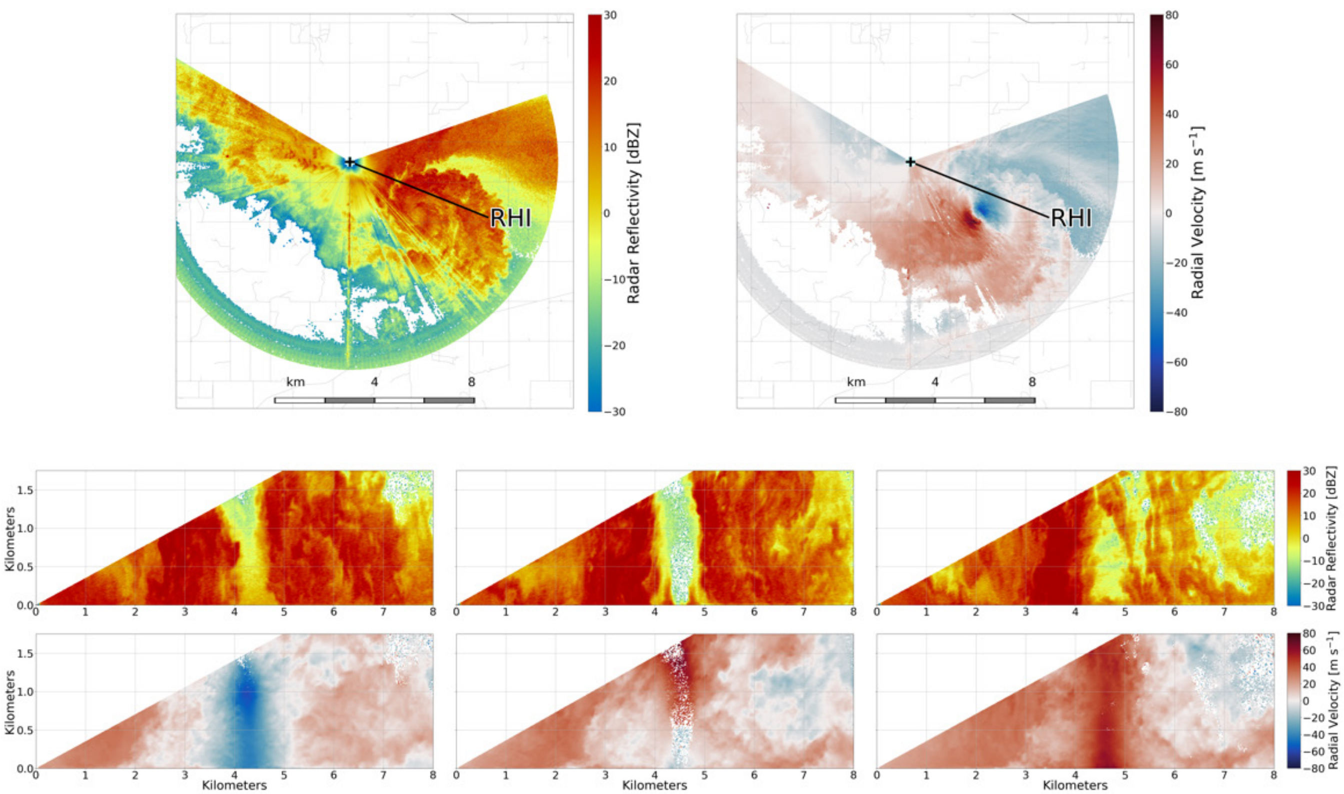


Figure 2-120: Texas Tech Ka-band mobile Doppler radar 0.33 deg PPI (upper left) reflectivity (dBZ) and (upper right) radial velocity (m s^{-1}), and RHI reflectivity (dBZ) and radial velocity (m s^{-1}) (bottom left) on the north side, (bottom center) through the middle, and (bottom right) on the south side of the Eldorado, OK, tornado on 23 May 2024.

ii Mesoscale and Stormscale Modeling Research

CIWRO has made significant contributions to NOAA's mission of accurate, timely, and actionable forecasts and warnings to the public. The research under this theme improved the forecasts of hazardous weather in NWS and advanced the understanding of storm physical processes by utilizing state-of-the-science data assimilation (DA) and modeling systems and atmospheric observations from various field campaigns.

A major activity under this theme was the development of NOAA's Warn-on-Forecast System (WoFS) which runs at 3-km grid spacing. The system was migrated from NSSL's inhouse supercomputer to cloud-based HPC using the latest technologies in cloud computing. Notably, the cloud-based WoFS set a unique example of a successful public–private partnership within NOAA. Additionally, we expanded the WoFS capability for smoke and fire hazards and evaluated the capability in NOAA's Fire Weather Testbed and Norman Forecast Office. The WoFS enables NWS forecasters, for the first time, to message probabilistic hazard information from individual thunderstorms between the watch-to-warning time frame within the United States. A key aspect of our effort was to transfer the cloud-based WoFS to NWS OSTI for phase 1 capability demonstration. CIWRO played a key role in NOAA's decision to replace FV3 model with NCAR's Model for Prediction Across Scales-Atmosphere (MPAS) dynamical model core for regional convective-scale Rapid Refresh Forecast System and WoFS under the Unified Forecast System framework. CIWRO spearheaded the MPAS model development for regional convective-scale application, evaluated the model in HWT SFE and developed MPAS based WoFS at 3-km cell spacing, which is set to replace the WRF model in WoFS. CIWRO has also been pursuing next-decade science for advancing the storm-scale prediction. CIWRO scientists developed the next-generation WoFS prototype at 1-km grid spacing which improves the prediction accuracy and reduces errors both in time and space compared to the 3-km WoFS. Furthermore, we are in the forefront of convective boundary layer research. The observations from emerging profiling instruments, such as infrared spectrometers, microwave radiometers, doppler lidars, and uncrewed aircraft systems are assessed using both observations system simulation experiments and WoFS for optimal profiler network design and improved prediction accuracy. Furthermore, we analyzed the data collected from various field campaigns to advance our understanding of storm-scale processes and interactions in various environments and conducted high resolution numerical simulations to understand and improve the predictability of severe thunderstorms and tornado potential.

CIWRO continues to develop cutting-edge prediction capabilities using the next-generation DA, modeling and observations, leveraging cloud HPC and machine-learning techniques. CIWRO's contribution is critical for advancing NOAA's goal to provide more accurate weather information to the American public and decrease vulnerability from hazardous and high-impact weather.

CIWRO Themes: Mesoscale and Stormscale Modeling, Forecast Application Improvements
CIWRO Contributors: Joshua Martin, Kent Knopfmeier, Brian Matilla, Derek Stratman, Patrick Skinner, Thomas Jones
Project Title: WoFS in the cloud
Relevance to NOAA: This project supports NOAA's mission by developing a next-generation water/weather modeling framework, optimizing platform-agnostic data and information, and supports the transition of infrastructure to cloud-based platforms.

The WoFS is migrated to a cloud-based, high-performance computing (HPC) system. All components of the system are containerized and a new, cloud-based workflow is developed on top of Azure's scalable Platform-as-a-Service (PaaS) offerings, enabling the execution of multiple WoFS domains simultaneously. A single web app facilitates the initiation, monitoring, and viewing of model runs, simplifying the process through an intuitive user interface. This interface greatly simplifies the administration of WoFS and grants designated users the ability to launch one or more WoFS domains from one screen. The WoFS framework can build the entire HPC environment on-demand, scale various web components, setup post-processing, and then finally remove the environment upon completion of the model run. With WoFS on the cloud, NSSL does not have to pay for any unused resources and also has access to the latest HPC technology. Cloud-based WoFS was successfully demonstrated during NOAA's HWT Spring Forecasting Experiments beginning in 2022 through 2024. Cloud computing provides an unmatched advantage for sporadic yet scalable applications, offering on-demand resources that expand to meet surges in usage, ensuring cost efficiency and optimal performance without the burden of maintaining continuous infrastructure. Tangible outcomes from this project include 1 formal journal article and 2 conference presentations.

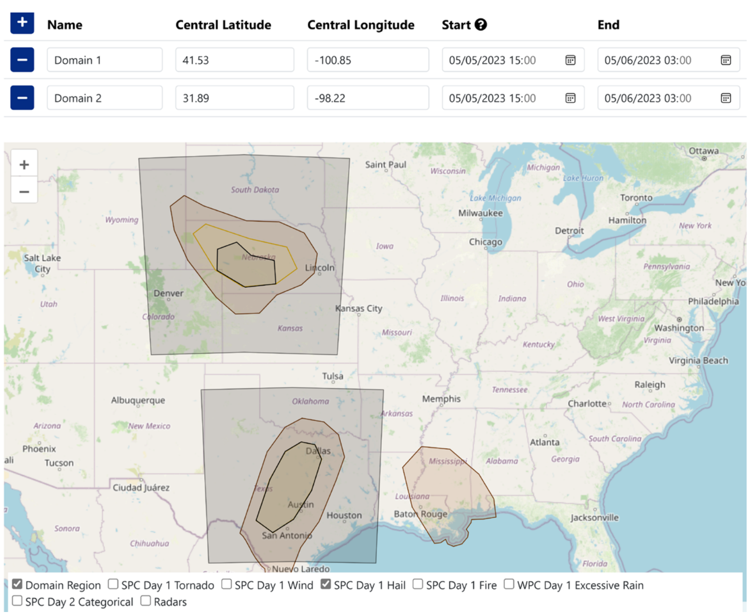


Figure 2-121: Screenshot of cb-WoFS Quick Launch screen, demonstrating how the screen would have appeared on 5 May 2023.

CIWRO Themes: Mesoscale and Stormscale Modeling, Forecast Application Improvements
CIWRO Contributors: Yunheng Wang, Larissa Reames, Thomas Jones, Kent Knopfmeier, Brian Matilla, Derek Stratman, Patrick Skinner, Nusrat Yussouf
Project Title: The development of MPAS-based WoFS
Relevance to NOAA: This project supports the NOAA mission by developing a next-generation water/weather modeling framework and improving weather and water predictions.

NSSL decided to replace the current Weather Research and Forecasting (WRF) model based WoFS with the next generation Model for Prediction Across Scales-Atmosphere (MPAS) dynamic core. The decision was motivated by the positive feedback from 2023 HWT Spring Forecasting Experiment evaluation of the NSSL-MPAS model runs over the contiguous United States. A prototype MPAS-WoFS is developed using the Ensemble Adjustment Kalman Filter technique from the Data Assimilation Research Testbed (DART) system and all features and capabilities of the current WoFS is incorporated. A software named MPASSIT is developed to interpolate the MPAS grid to a regular grid, such as lambert conformal conic or lat-lon. After addressing several numerical issues in the MPAS and DART, the MPAS-WoFS prototype is tested using 6 severe weather events from Spring 2024. Initial results from MPAS-WoFS shows promise. Tangible outcomes from this project include 4 conference presentations and 4 software releases. This project is a collaborative effort involving NCAR and NOAA/GSL.

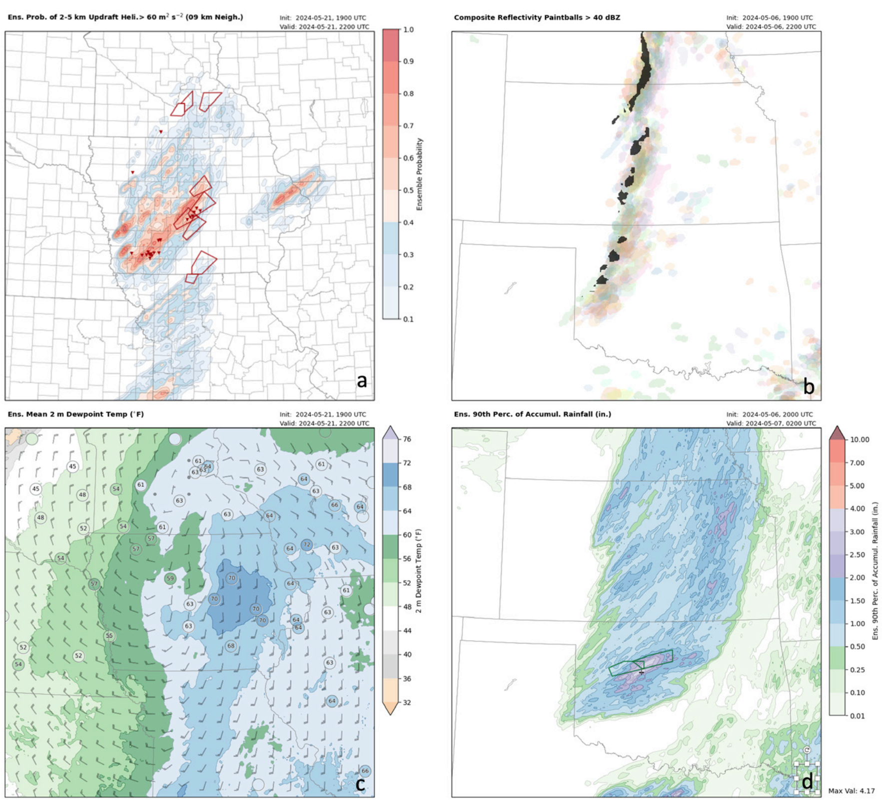
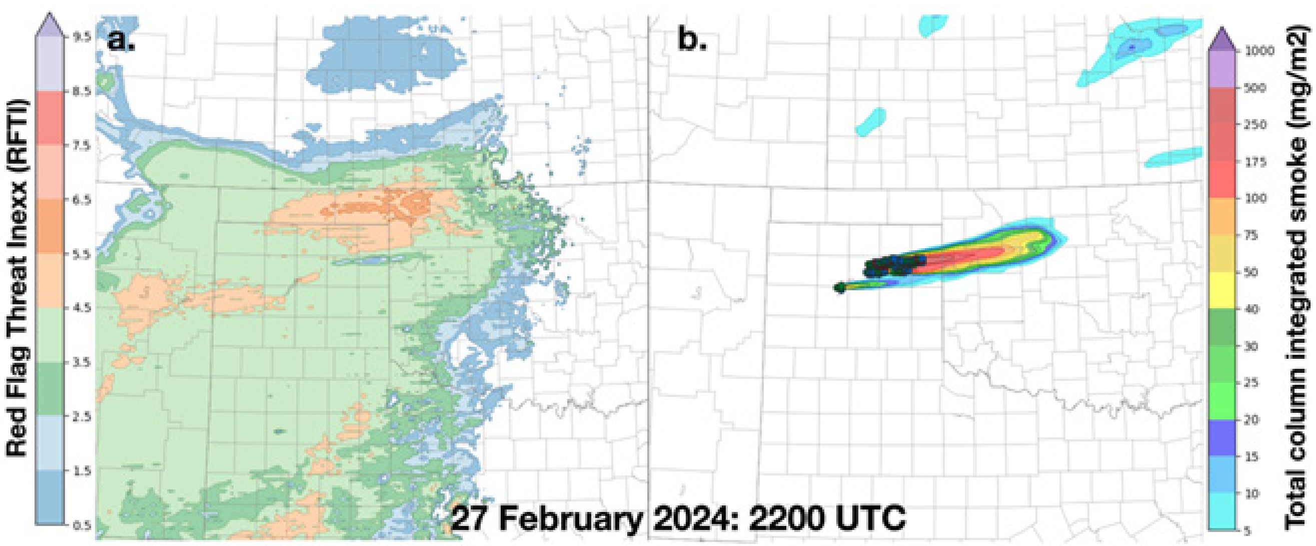


Figure 2-122: Example 3-h forecast a) ensemble probability of 2–5-km UH >60 m^2s^{-2} (with NWS tornado reports and warning polygons overlaid), b) composite reflectivity paintballs exceeding 40 dBZ with MRMS reflectivity > 40 dBZ overlaid (black), c) ensemble mean of 2-m dewpoint temperature (^oF) with surface observations overlaid in circles, and d) 6-h forecast ensemble 90th percentile accumulated rainfall (with flash flood warning polygons overlaid) from May 21 and May 06 in 2024.

CIWRO Themes: Mesoscale and Stormscale Modeling, Forecast Application Improvements
CIWRO Contributors: Thomas Jones, Patrick Skinner, Brian Matilla, Kent Knopfmeier, Joshua Martin, Fangjiao Ma.
Project Title: Improving forecasts of wildfire environments and smoke emissions using WoFS-Smoke
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions, developing reliable probabilistic guidance products, and improving continuous engagement with partners.

To improve forecasting of fire weather related conditions including the pre-fire environment, active fire smoke transport, and heavy precipitation in burned regions, the 3 km WoFS has been extended to form WoFS-Smoke (Jones et al. 2022a, b; 2024). WoFS-Smoke uses fire radiative power (FRP) retrievals from GOES-16/18 satellites to introduce smoke emissions into the system with an update frequency of 15 minutes. Several products have been developed for the system that include new environmental and smoke concentration forecasts (see Figure). One example is a new Red Flag Threat Index (RFTI) parameter that is suitable to WoFS applications using an hourly re-analysis for environmental backgrounds (Jones et al., 2025). The initial version of the system was evaluated in coordination with the Fire Weather Testbed in November 2023 and later with NWS forecast offices in 2024 (Hatchett et al. 2024). Ongoing work to extend the system include testing of Next Generation Fire System (NGFS) satellite retrievals from NESDIS/CIMSS in place of the standard GOES product and linking buoyancy estimates generated as part of the plume-rise and smoke emissions model back to the vertical velocity variable. Tangible outcomes include 5 journal articles, 5 conference presentations and 1post-doctoral research scientist. External partners involved in this project include NOAA/GSL, NWS, NESDIS and CIMSS.



Figure

Figure 2-123: Examples of 1 hour forecast valid at 2200 UTC 27 February 2024 of ensemble mean RFTI (a) and total column smoke aerosol concentration (b). Dots represent the location of GOES-16 FRP retrievals at the forecast initiation time of 2100 UTC. Higher values of RFTI indicate a more favorable environment for wildfire spread.

CIWRO Themes: Mesoscale and Stormscale Modeling, Forecast Application Improvements
CIWRO Contributors: Christopher Kerr, Derek Stratman, Patrick Skinner, Nusrat Yussouf, Brian Matilla, Yunheng Wang, Yaping Wang
Project Title: Development of a WoFS with a 1-km horizontal model grid spacing
Relevance to NOAA: This project supports the NOAA mission by developing a next-generation water/weather modeling framework and improving weather and water predictions

The NSSL WoFS provides short-term ensemble forecasts (0-6 hours) of individual thunderstorms to bridge the gap between severe weather watches and warnings. The first version of WoFS nearing operations has a 3-km horizontal model grid spacing (WoFS-3km). Since 2021, another version of WoFS with a 1-km horizontal model grid spacing (WoFS-1km) has been under development with over 30 case studies completed to date. A higher resolution system will eventually replace WoFS-3km. Results have shown WoFS-1km better resolves smaller thunderstorms (< 400 km^2) while also better depicting rotation within convective storms. These small thunderstorms can produce high-impact hazards including strong tornadoes. While WoFS-1km can better detect a subset of convective storms, it also depicts storms more realistically than WoFS-3km. Storms within WoFS-1km have smaller displacement and size errors than in WoFS-3km. Visually, storms appear more realistic in WoFS-1km as well. This is supported by small storm solidity errors. Tangible outcomes from this project include 4 formal journal articles, 5 conference presentations and 1post-doctoral research scientist.

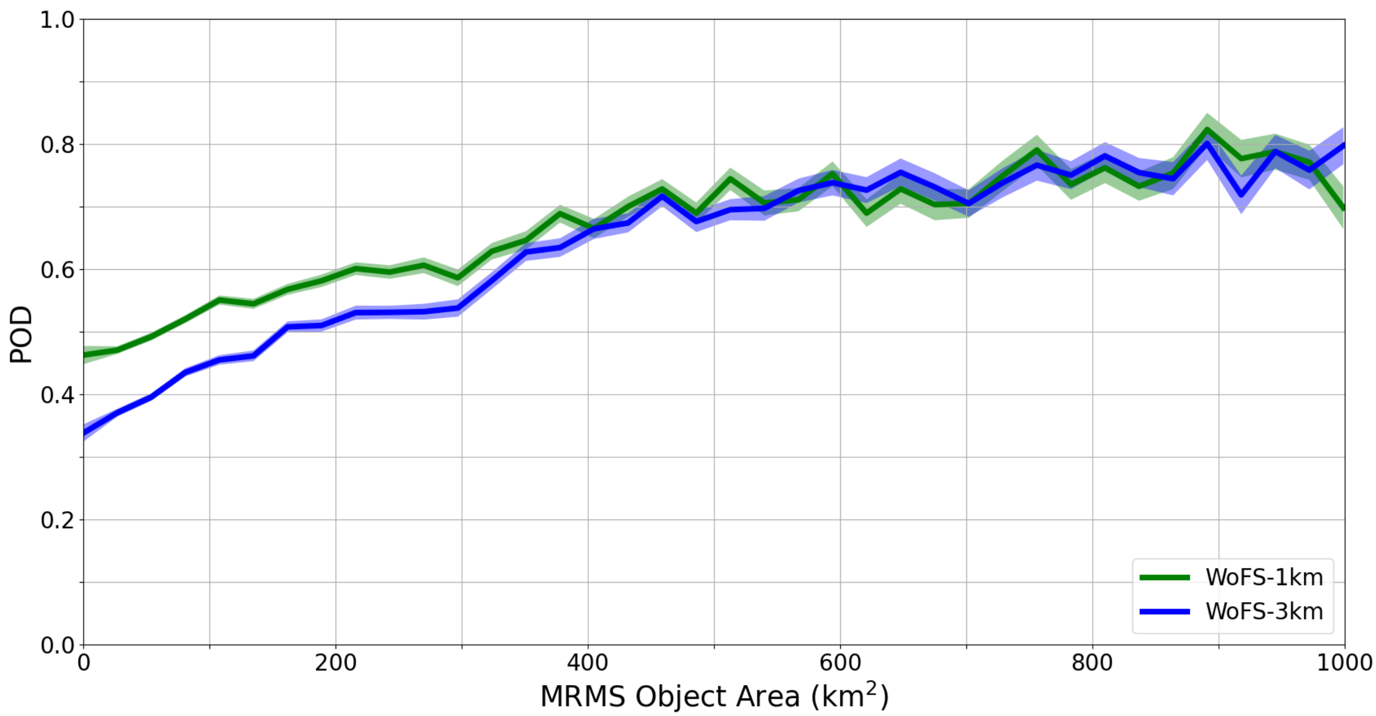


Figure 2-124: Probability of detection (POD) of composite reflectivity storm objects for WoFS-1km (green) and WoFS-3km (blue) as a function of the observed storm object area. Statistical significance is denoted by the shading around each line. WoFS-1km has higher POD for storms < ~400 km^2. Figure adapted from Kerr et al. (2024).

CIWRO Themes: Mesoscale and Stormscale Modeling, Forecast Application Improvements
CIWRO Contributors: Kelsey Britt, Patrick Skinner, Monte Flora, Brian Matilla, Kent Knopfmeier
Project Title: Verification of quasi-linear convective systems predicted by WoFS
Relevance to NOAA: This project supports the NOAA mission by creating/improving a trusted analysis of record for model verification/nowcasting, improving weather and water predictions, and developing reliable probabilistic guidance products.

Quasi-linear convective systems, also known as squall lines, can produce multiple hazards such as flash flooding, straight-line winds, and tornadoes, posing a significant risk to life and property. Additionally, these systems are often difficult to accurately forecast. This study systematically evaluates the quality and performance of squall line forecasts generated by the WoFS, a convection-allowing ensemble prediction system. Results from Britt et al. (2024) indicate that WoFS demonstrates skill in forecasting squall lines up to six hours in advance. Compared to forecasts for all storm types, squall line forecasts generally had higher probabilities of detection and lower false alarms. However, WoFS tended to overpredict the intensity of squall line features, such as the northern bookend circulation and the rear-inflow jet. This overprediction may have implications for squall line hazard prediction, particularly for tornadoes, warranting further investigation. Tangible outcomes include one formal journal publication and four conference presentations. One Ph.D. student was supported and advised during this project.

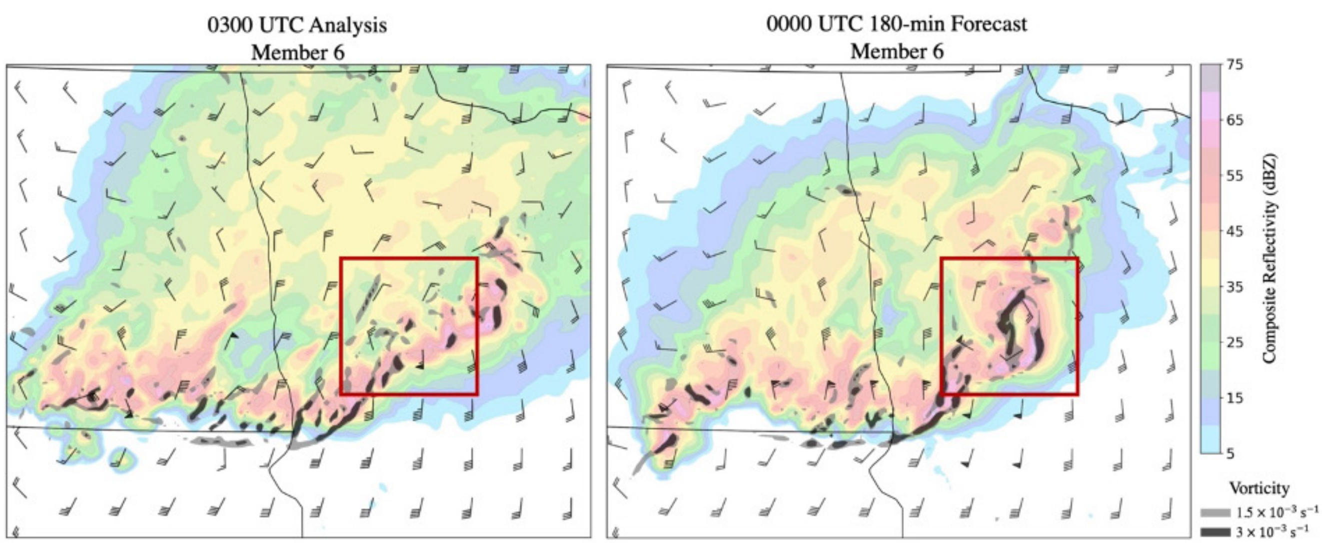


Figure 2-125: Composite reflectivity, winds, and vorticity for the 17 July 2020 squall line event. The analysis (i.e., closest to observations) for WoFS's ensemble member 6 (left) is compared to the 180-min forecast for the same member (right). The forecast shows an intense northern bookend circulation located within the red box, which is not present in the analysis.

CIWRO Themes: Mesoscale and Stormscale Modeling, Weather Radar and Observations, Forecast Application Improvements
CIWRO Contributors: Derek Stratman, Nusrat Yussouf, Chris Kerr, Brian Matilla, Yunheng Wang, Yaping Wang
Project Title: Using stochastic and perturbed parameters in model physics parameterized schemes to assimilate NSSL's PAR observations into WoFS
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and developing a next-generation water/weather modeling framework

The success of WoFS to provide useful probabilistic guidance of severe and hazardous weather is mostly due to the frequent assimilation of observations, especially radar observations. The PAR technology would allow for even more rapid assimilation of radar observations by providing full-volumetric scans of the atmosphere every ~1 min. Past studies show more frequent PAR data assimilation can lead to improved forecasts, but it can also lead to ensemble underdispersion and suboptimal observation assimilation. In this project, stochastic and perturbed parameter methods were assessed as a potential solution to this problem by increasing the ensemble spread in a 1-km version of the WoFS. Results revealed the potential benefits of these methods. For example, these methods can lead to more skillful forecasts during periods of storm development, when WoFS can benefit from the assimilation of frequent PAR observations. Tangible outcomes from this project include 1 formal journal article and 2 conference presentations.

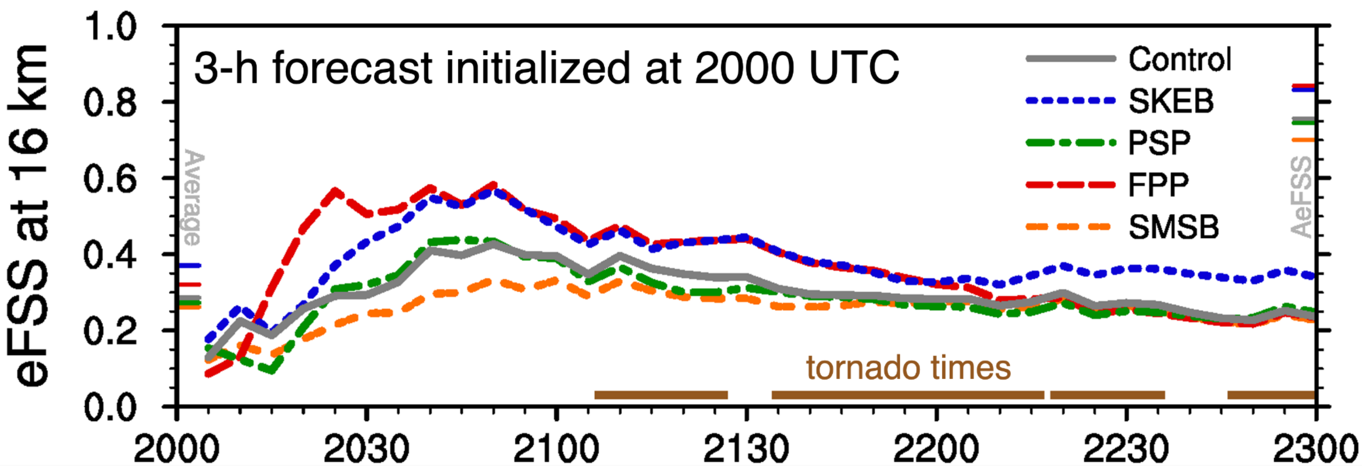


Figure 2-126: Ensemble fractions skill score (eFSS) for 3-h forecasts on 9 May 2016 for a Control experiment and four stochastic and perturbed parameter experiments – SKEB, PSP, FPP, and SMSB. Average eFSS and asymptotic eFSS are indicated on the left and right sides, respectively. The times of the tornadoes produced by the two storms of interest are represented by the brown lines. eFSS values closer to 1 are better. Figure adapted from Stratman et al. (2024).

CIWRO Themes: Mesoscale and Stormscale Modeling, Weather Radar and Observations
CIWRO Contributors: Jordan Tweedie, Nusrat Yussouf, Yaping Wang, Tyler Bell
Project Title: Impacts of assimilating Unmanned Aerial Systems (UAS) measurements in the Warn-on-Forecast System
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and developing next-generation observational capabilities.

One limitation of the convection-allowing modeling system is the inadequate representation of storm environments in model initial conditions, particularly in the atmospheric boundary layer (ABL). This is largely due to the unavailability of high spatial and temporal resolution ABL observations. In recent years, the emerging UAS have shown promise in measuring the ABL temperature, moisture, and winds. This study conducts several ensemble data assimilation and prediction experiments to assimilate UAS measurements from the 2022–2023 Propagation, Evolution, and Rotation in Linear Storms (PERiLS) field campaigns in WoFS. The goal is to assess how these lower atmospheric (~0–2 km AGL) boundary layer measurements from UAS impact WoFS' short-term probabilistic predictions of the environment and hazards associated with severe weather. Results show that the addition of UAS observations enhances the short-range prediction of rotation in tornadic storms. Specifically, UAS observations help to more accurately identify areas of increased low-level moisture and wind convergence, which improves the timing, placement, severity, and probability of storms. Tangible outcomes from this project include 1 Master's thesis and 3 conference presentations. 1 GRA, who has transitioned to a Research Fellow, is supported by this project.

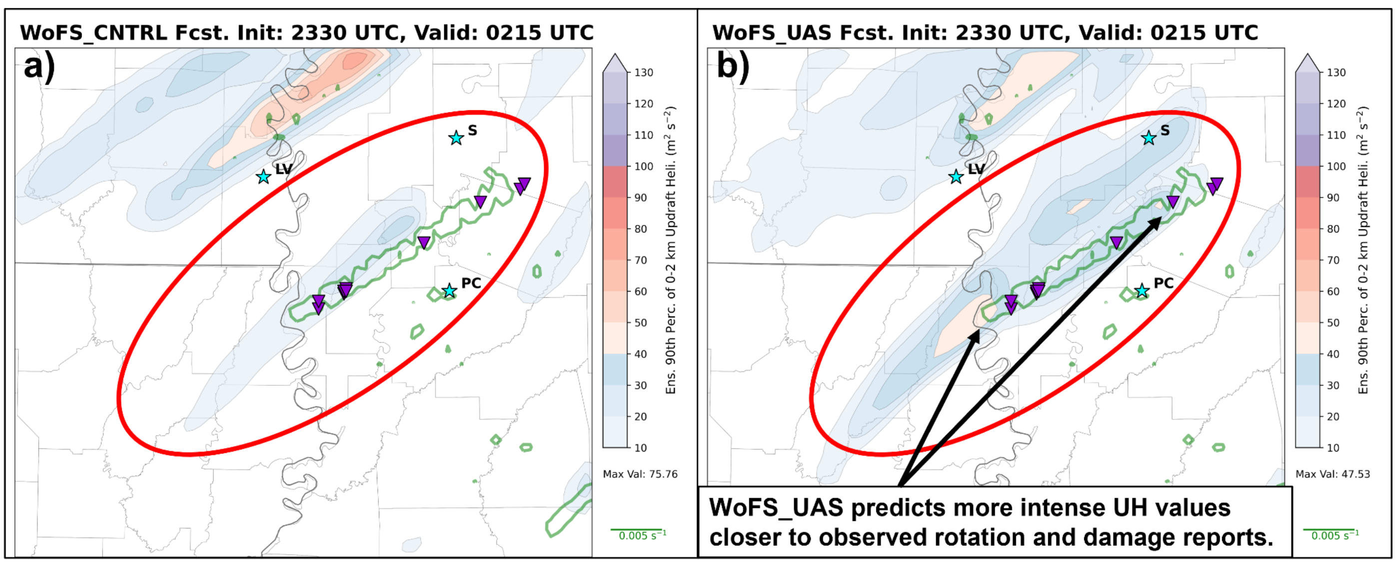


Figure 2-127: Example of (a) WoFS_CNTRL and (b) WoFS_UAS 165-min forecasts of the ensemble 90th percentile of 0–2 km updraft helicity (UH) >20 $m^2 s^{-2}$ for the 23–24 March 2023 Rolling Fork EF4 tornado event. Overlaid green contours are observed MRMS 0–2 km azimuthal wind shear > 0.005 s^{-1}, purple triangles are NWS tornado damage reports, and cyan stars are the three UAS profiling sites.

CIWRO Themes: Mesoscale and Stormscale Modeling, Forecast Application Improvements
CIWRO Contributors: Joshua Gebauer, Tyler Bell, Antonio Segales, Lydia Bunting, Matthew Ammon
Project Title: Venturing into the vertical: optimizing vertical profiling in mesonets
Relevance to NOAA: This project supports the NOAA mission by developing next generation observational capabilities and improving weather and water predictions.

This project funded by the WPO Observation Program evaluates the optimal design of a boundary layer profiling network using observations simulation system simulation experiments with realistic observations simulators of infrared spectrometers, microwave radiometers, Doppler lidars, and uncrewed aircraft systems that were developed for this project. The OSSEs conducted for this project replicate the NSSL Warn-on-Forecast system. The project developed a unique ensemble nature run framework that provides a measure of the intrinsic predictability of the events that are being forecasted (Gibbs et al. 2025). Initial results from OSSEs of two simulated convective events has identified that including a profiling of components to the Oklahoma mesonet would improve the representation of the strongest storms in short term forecasts. However, the impact of the simulated mesonet is short lived for these convective events due to the limited area that they cover. This ongoing project has so far resulted in 1 journal article that is under review, and 1 conference presentation. The project has supported 1 graduate research assistant, and 2 undergraduate researchers.

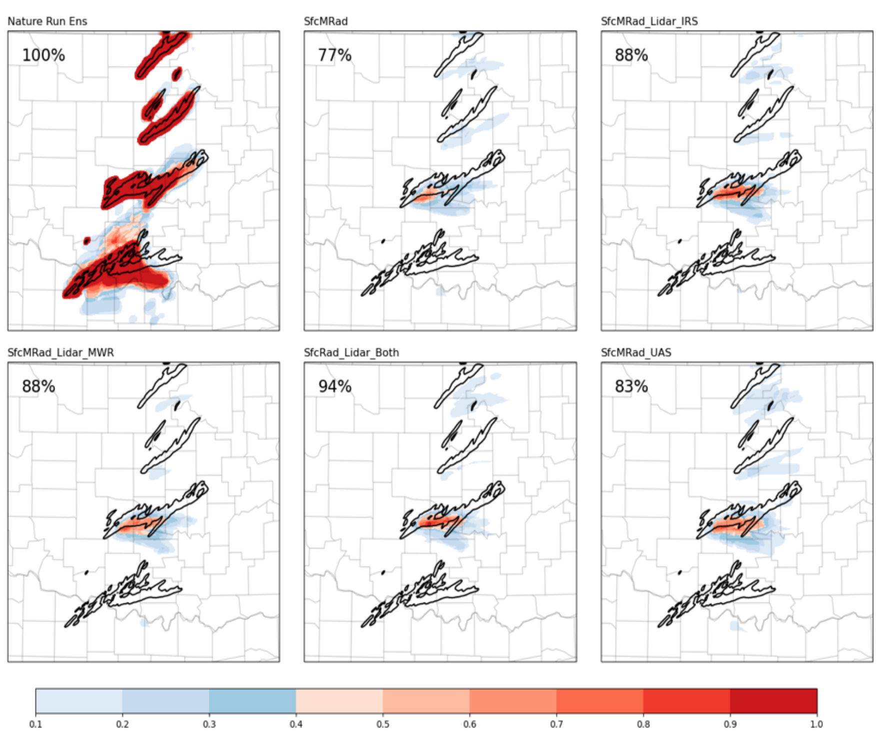


Figure 2-128: Ensemble probability of 2-5 km updraft helicity greater than 150 m^2 s^{-2} the nature run ensemble and experiment that assimilate simulated infrared spectrometers, microwave radiometers, lidar, and UAS. The swaths of 2-5 km updraft helicity greater than 150 m^2 s^{-2} from the nature run is contoured in black. The maximum probability in each experiment is annotated on each plot.

CIWRO Theme: Mesoscale and Stormscale Modeling
CIWRO Contributors: Martin Satrio, Bobby Saba, Tyler Pardun
Project Title: The effects of backing winds within the effective inflow layer on supercells and tornado-like vortices in CM1
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions.

The presence of backing layers within an otherwise veering wind profile create veer-back-veer (VBV) profiles that are occasionally observed in severe storm and supercell environments. While anecdotally thought to be detrimental to supercell strength and tornadogenesis likelihood, limited work on the matter (e.g., Parker 2017) show backing layers rooted *above* the effective inflow layer (EIL) have little effect on storm evolution. This work composites observed profiles from the surface objective analysis scheme to explore how backed winds rooted *within* the EIL affects supercell evolution within CM1. Preliminary findings from this work show that the presence of a backed layer within the EIL does indeed have influence on supercell evolution, including consequences on tornado-like vortex (TLV) formation and behavior. Namely, the supercell within the control simulation (exp A; no backed layer) has a faster forward motion, with a rightward deviation occurring earlier in the simulation compared to the simulation with a backed layer (exp B). Additionally, the overall storm and updraft is larger in exp A, even after the storm erodes the backed layer through storm-induced accelerations in exp B. TLVs in exp A are more robust in strength, depth, and longevity, with TLVs in exp B struggling to maintain themselves. While future work involves running simulations with a more realistic boundary layer and utilizing an ensemble approach, preliminary results indicate that backing layers within the EIL may be detrimental to supercell strength and TLV production. This work has resulted in 1 conference presentation with the involvement of 2 GRAs.

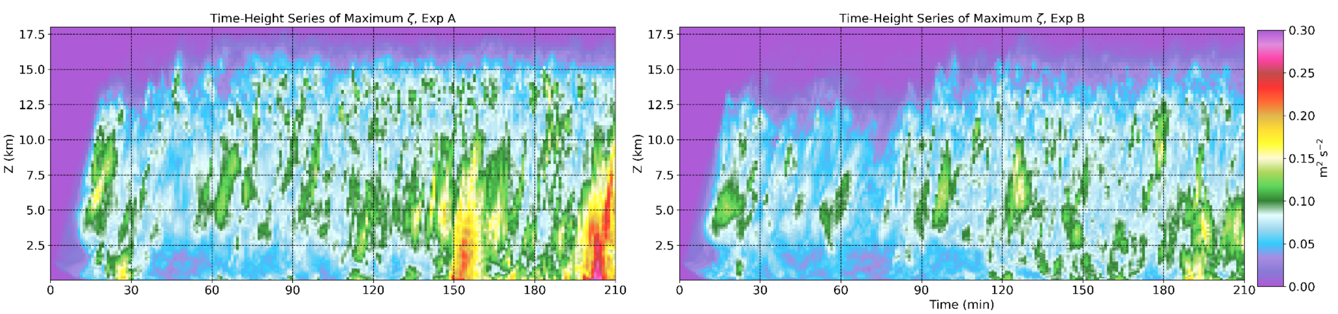


Figure 2-129: Time-height series of maximum vertical vorticity (colored) from experiment A with no backed layer (left) and experiment B with a backed layer (right).

CIWRO Themes: Mesoscale and Stormscale Modeling, Weather Radar and Observations
CIWRO Contributors: Alexander Ryzhkov, Maci Gibson, Jiaxi Hu, Savannah Southward
Project Title: Observational and numerical modeling study of downburst generation using dual-polarization radar
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the RadarNext program and/or WSR-88Ds and developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

We develop an idealized one-dimensional model of downburst development with bin microphysics and a coupled polarimetric radar forward operator to study the relationships between proposed downburst radar signatures (such as descending Z and K_{DP} cores) and forcing mechanisms (i.e., precipitation loading and diabatic cooling). The model is able to realistically reproduce observed downburst radar signatures and evolution, with precipitation loading being the dominant close to the 0°C level and diabatic cooling becoming dominant closer to the surface. The model is described in the journal article of J. Carlin and A. Ryzhkov "What can polarimetric radar signatures of developing downbursts reveal about their intensity?". In addition to theoretical modeling, an algorithm for polarimetric downburst detection is under development. A random forest algorithm trained on a large number of downburst events observed with the WSR-88D radars yields promising results. It identifies upper-level Z, maximum K_{DP}, and mid-level convergence as the most important predictor variables, in line with conceptual models of downbursts. The model and observational results create the basis for predicting the strength of "cold pools" in thunderstorms and tornadic events and provide guidance for capitalizing on the unique benefits of the phased-array radars.

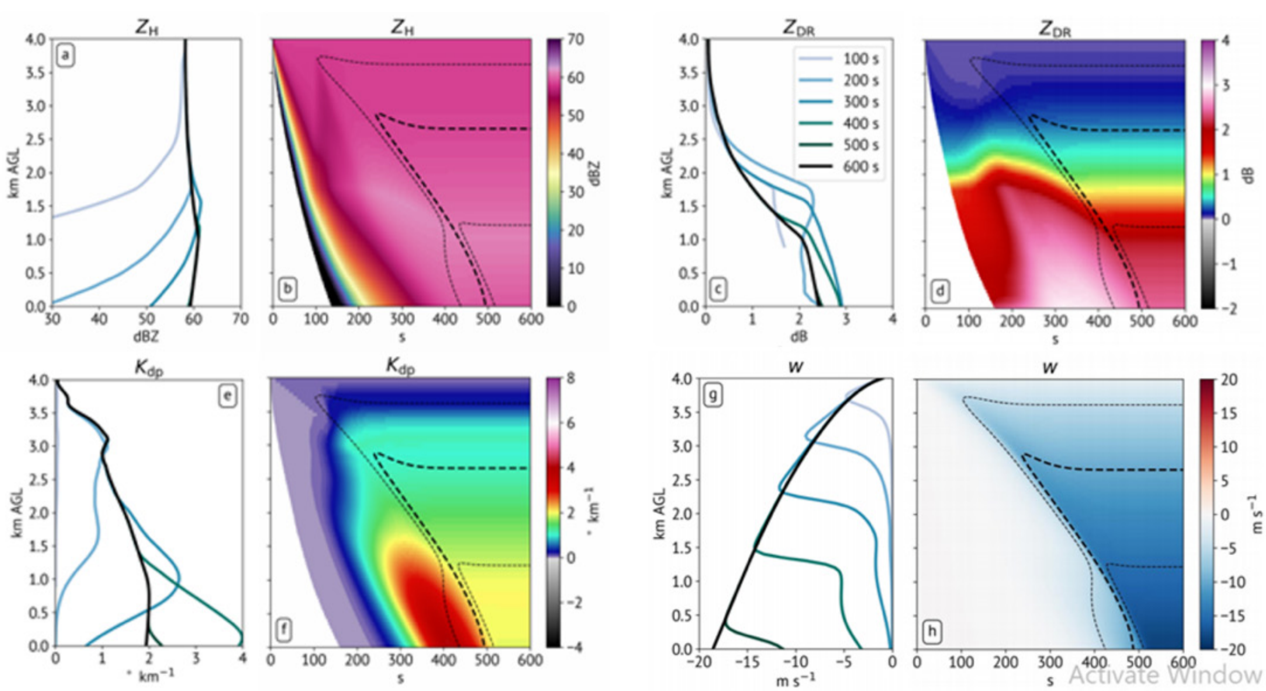


Figure 2-130: Vertical profiles (every 100 s) and time-height plots of simulated Z, Z_{DR}, K_{DP}, and downdraft velocity w simulated from the model.

CIWRO Themes: Mesoscale and Stormscale Modeling, Forecast Application Improvements
CIWRO Contributors: Jeffrey Milne, David Jahn, Andrew Wade
Project Title: Identification and verification of mesoscale convective systems in the models of the high-resolution ensemble forecast system
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions

Mesoscale convective systems (MCSs) are large (100+km) organized thunderstorms that are often associated with severe wind and tornadoes. While an initial attempt to identify MCSs solely through shape characteristics was unsuccessful, the analysis performed did demonstrate that there are some fundamental differences between the shapes of modeled and observed storms, particularly the orientation angle. This held true for all members of the High Resolution Ensemble Forecast System (HREF), a multi-model, multi-physics convection-allowing ensemble used operationally. An MCS identification algorithm was ultimately developed based on an observational algorithm that is used to identify MCSs in near-real time by the SPC. The parameters of the algorithm were tuned to match expert labeling of modeled storms. Comparing modeled and observed storms for an entire year showed that the models failed to reproduce both the diurnal and annual cycle of MCSs seen in observations. When matching forecast to observed MCSs, the forecasts were in a high success ratio/low probability of detection regime. This indicates that, when a model does forecast an MCS, one usually occurs, but the model does not forecast enough MCSs. Work is ongoing to use this information and algorithm to develop an operational MCS forecasting product. This project supported 1 graduate student. The SPC was the sole external partner of this project.

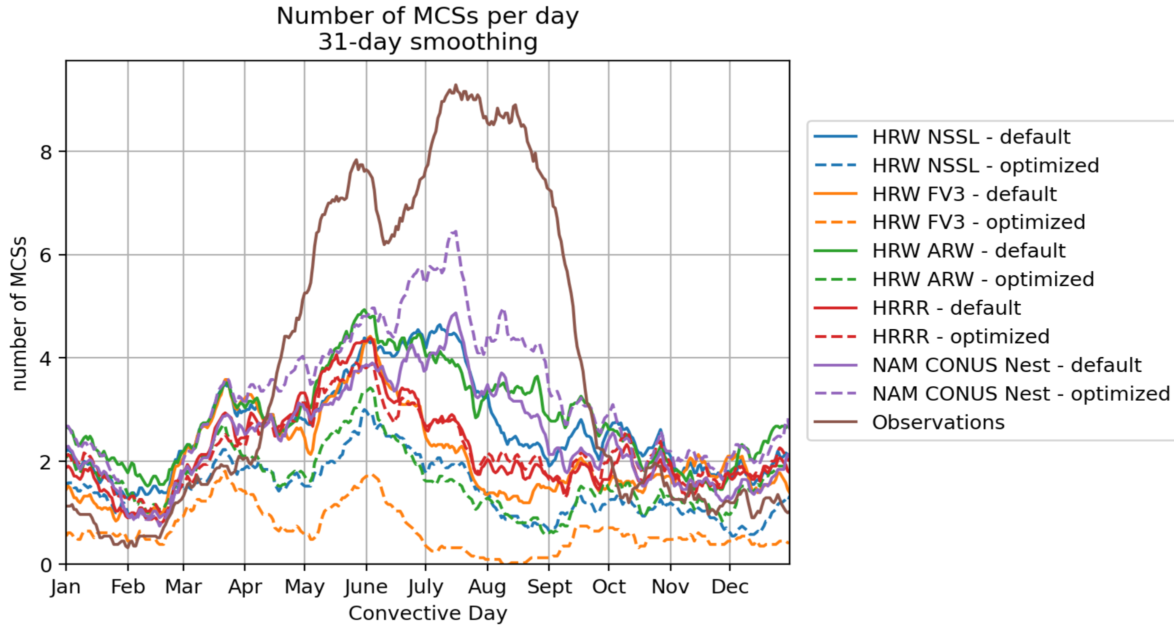


Figure 2-131: The number of MCSs per day in observations (brown) and the models (colors). An underforecast can be seen throughout the year. The maximum number of observed MCSs coincides with a decline or minimum in the modeled number of MCSs.

CIWRO Themes: Mesoscale and Stormscale Modeling, Forecast Application Improvements
CIWRO Contributor: Jeffrey Milne
Project Title: Exploring a new method of calculating updraft helicity
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions

Updraft helicity (UH) is a commonly used diagnostic in convection allowing forecast models because UH swaths are associated with severe weather reports. UH is defined as the vertical integral of the product of vertical velocity and vertical vorticity and is most commonly calculated over the 2-5km AGL layer (0-3km and 1-6km are also commonly used layers). To attempt to improve UH forecasts, the vertical structure of vertical velocity, vertical vorticity, and the product of vertical velocity and vertical vorticity was explored. This showed that ample vertical velocity and vertical vorticity existed outside of the 2-5km layer and that the structure of those quantities varied depending on the type of storm being simulated. To capture the full range of the distribution of vertical velocity and vertical vorticity, the UH calculation was modified to integrate over a variable layer from the surface to the lowest level of downward vertical velocity instead of integrating over a fixed layer. The variable-layer method of calculating UH showed higher magnitudes associated with the most intense updrafts in idealized simulations, and it was hypothesized that this would correlate better with observed severe weather than the fixed-layer UH calculation. When applied to real-world simulations, however, the variable-layer UH calculation did not improve severe weather forecasts over the fixed-layer UH calculation. Tangible outcomes from this project include 3 conference presentations. This project supported 1 graduate student. The SPC was the sole external partner of this project.

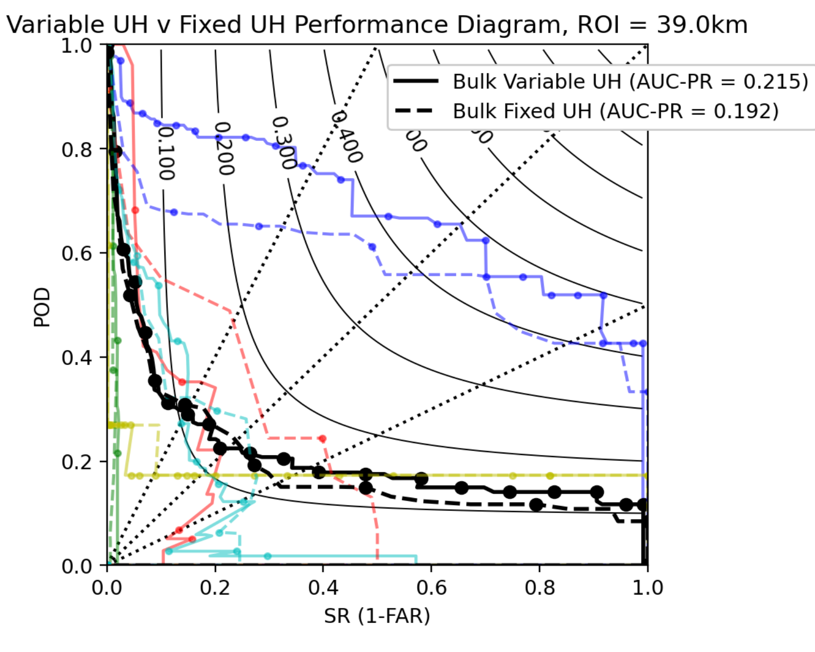


Figure 2-132: A comparison of forecast performance of fixed-layer and variable-layer UH for 5 cases (colors) and in bulk when aggregating the 5 cases (black). The slight improvement in bulk for the variable-layer UH comes entirely from a single case (blue). In the other 4 cases, the fixed-layer UH outperformed the variable-layer UH.

CIWRO Themes: Mesoscale and Stormscale Modeling, Weather Radar and Observations
CIWRO Contributor: Lauren Pounds
Project Title: Analysis of hail production and hail model sensitivity via simulated hailstone trajectories
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions.

Pounds et al. (2024) shows the findings from hundreds of thousands of hailstone trajectories. Rather than using model fields to generate hailstone trajectories, radar observations (multi-Doppler analyses) and Diabatic Lagrangian analyses (DLA) were used. It was found that the largest hailstones reside within the downshear deacceleration zone (DDZ) where the hailsone and the updraft are in balance and residence time can be extended. In efforts to improve the hail model, Pounds et al. (2025) (in internal review) performed multiple sensitivity analyses. The sensitivity analyses showed oblate hailstones are closer to reality than spherical hailstones (which most hail models use). This work has resulted in two conference presentations and one journal article.

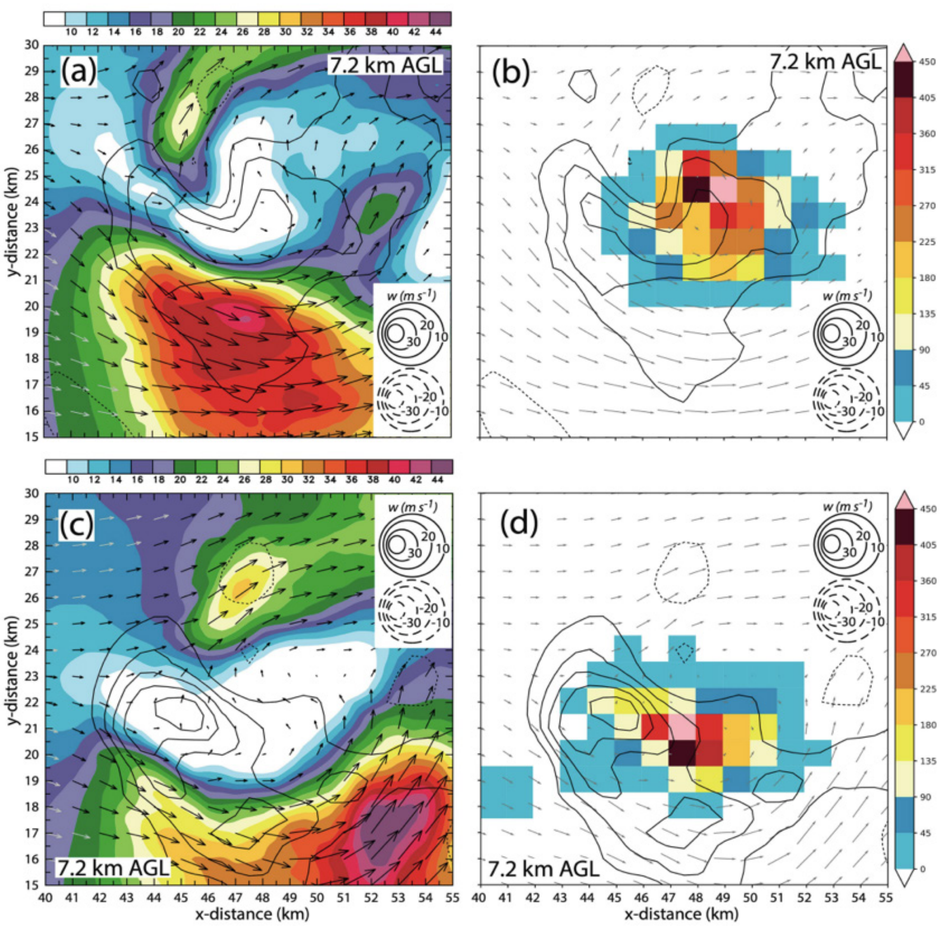


Figure 2-133: Horizontal and vertical air speeds relative to severe hail concentrations at 7.2 km AGL at (a),(b) 2315 and (c),(d) 2345 UTC. (left) Horizontal wind speed exceeding 10 m/s and (right) column-integrated severe hail concentration. Black contours (solid 5 positive, dotted 5 negative) are vertical velocity (m/s) with contour levels indicated by the inset. Vectors are storm-relative horizontal airflow.

CIWRO Themes: Mesoscale and Stormscale Modeling, Weather Radar and Observations
CIWRO Contributor: Morgan Schneider
Project Title: Mesovortex evolution in a simulated QLCS-supercell merger
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions.

Mergers between squall lines and supercells have been linked to the formation and intensification of mesovortices, but few studies have sought to address the dynamics of these interactions. In this work, idealized simulations are used to study the evolution of rotation in a mesovortex during a squall line-supercell merger. The rotation that develops from the remnant supercell mesocyclone is stronger, deeper, and more persistent than rotation in a non-merging squall line, suggesting that the merger enhances rotation intensification, and that the mesovortex retains some of its supercellular characteristics. Trajectory analysis reveals that air from the environment cycles through a strong downdraft before entering the mesovortex, but that mechanisms for rotation generation vary over the course of the merger. Storm features and structures typically seen in either supercells or squall lines are both present in the merger mesovortex, implying that mesovortices in squall line-supercell mergers may be characterized by a combination of both supercell-like and squall line-like processes. This project is ongoing and has resulted one conference presentation.

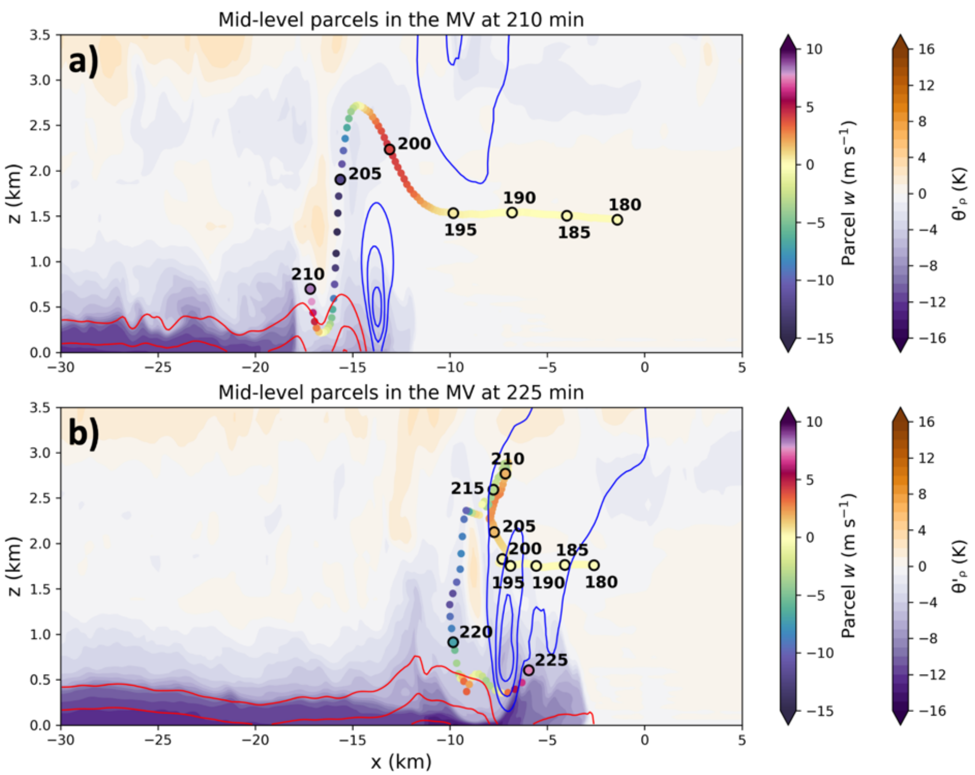


Figure 2-134: Vertical cross sections of potential temperature perturbation (shaded) and pressure perturbation (contoured every 1 hPa, with red denoting positive and blue denoting negative perturbations) at times (a) just before the merger and (b) after the merger, with select median air trajectories overlaid (colored by vertical wind speed). Time is annotated every 5 min along the trajectories.

CIWRO Theme: Mesoscale and Stormscale Modeling
CIWRO Contributor: Dominic Candela
Project Title: Understanding the influence of land cover transitions on tornadoes through high resolution simulations and damage analysis from uncrewed aircraft systems
Relevance to NOAA: This project supports the NOAA mission by developing next-generation observational capabilities and improving weather and water predictions.

The goal of this project is to better understand the interaction between tornadoes and heterogeneous land cover. This study utilizes Cloud Model 1 (CM1) to perform high resolution numerical simulations of a tornado translating over various surface roughness distributions. The simulations are inspired by unique damage instances captured by the NSSL-CIWRO damage assessment team from the Rolling Fork, MS, tornado. The simulations particularly focus on an instance where the tornado progressed through an isolated patch of trees. As the tornado exited the patch of trees a northern shift and widening of the path occurred (Figure a). Simulation results have shown a change in structure of the vortex as it progresses over the higher surface roughness area with a more disorganized inner core and a decrease in aerial extent of the highest velocity (Figure b). The simulations have not shown a significant shift in the path upon exit, but a widening of the maximum winds and treefall was found. This ongoing project has resulted in 1 conference presentation and is in collaboration with David Bodine (SoM/ARRC).

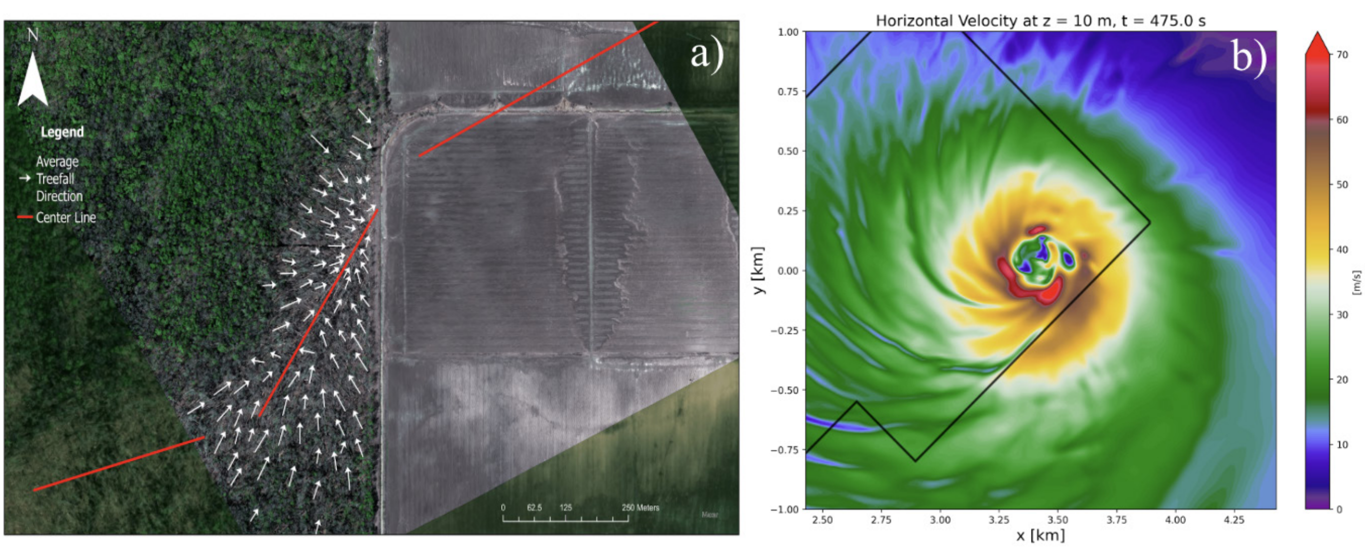


Figure 2-135: Path of the Rolling Fork tornado captured from UAS as it exited a patch of trees (a). Horizontal velocity in the simulation as the tornado is about to exit the higher surface roughness (b). Black contour lines indicate the surface roughness distribution.

CIWRO Theme: Mesoscale and Stormscale Modeling
CIWRO Collaborator: Sreenath Paleri
Project Title: Simple model for near surface energy fluxes
Relevance to NOAA: This project supports the NOAA mission by optimizing platform-agnostic data and information and improving weather and water predictions.

This research aims to produce a generalized model for near surface fluxes, using only routinely measured mean meteorological variables. This will help to estimate surface heat fluxes at high confidence with much lower cost and simple measurement techniques. This method is now being evaluated at ATDD surface flux stations with differing vegetation and terrain conditions. Tangible outcomes from this project include one conference presentation. External partners involved in this project include Texas Tech University.

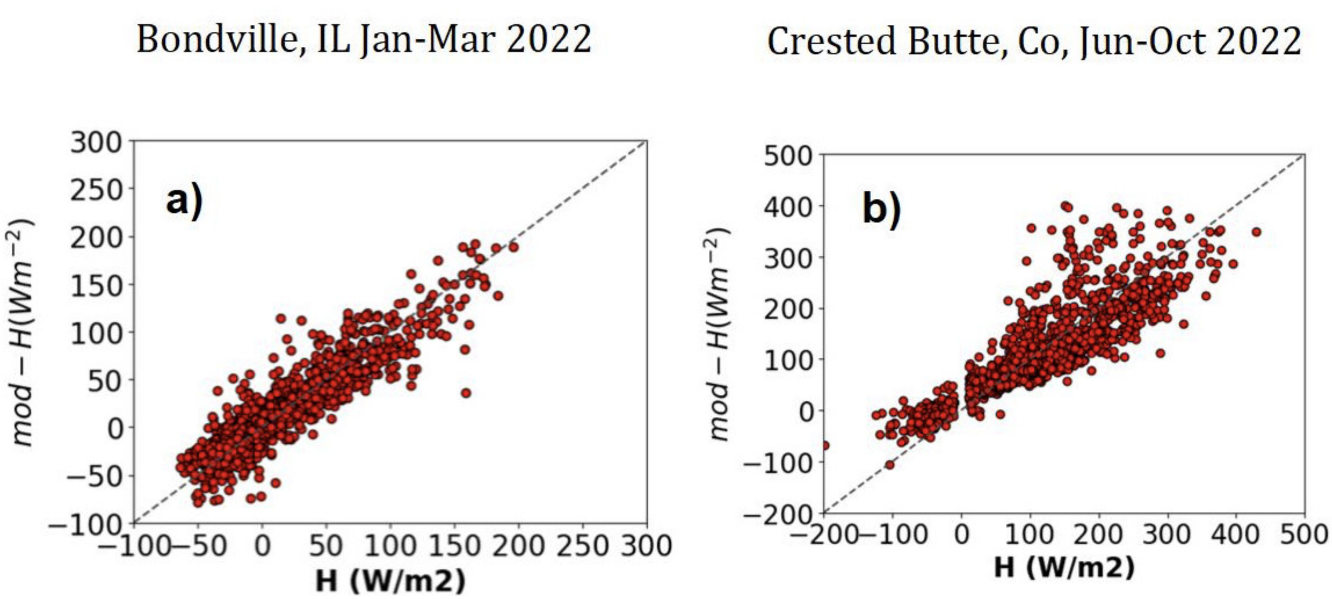


Figure 2-136: Measured vs modeled heat fluxes for an ideal, simple soybean/corn canopy at Bondville, Illinois (a) and for a complex, mountain site at Kettle Ponds, Colorado (b). Data collected in the summer for both sites.

CIWRO Theme: Mesoscale and Stormscale Modeling
CIWRO Contributors: Xuguang Wang, Yongming Wang
Project Title: Development and research of machine learning on data assimilation for convective-cale “Warn-on-Forecast”
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and maturing the next-generation earth system models

We use machine learning (ML) to construct heterogeneous convective-scale static background error covariances (BEC) in the hybrid Ensemble-variational (EnVar) data assimilation (DA) system to improve supercell predictions and to save the computational cost. A static BEC was developed by Wang and Wang (2021) for convective scale DA and is shown to improve the convective scale EnVar. This BEC (denoted as Z_BEC), however, cannot distinguish the error statistics and variable correlations for significantly different features within e.g. a supercell. This study leverages the ML algorithm, the random forest, to develop a new approach to allow the heterogeneous static BECs to be computed feature-dependently (denoted as ML-BEC). The impact of ML_BEC and Z_BEC is compared within 3DVar and hybrid EnVar frameworks using several tornadic supercell cases. Results (Fig. 1) show that, ML_BEC improves reflectivity forecasts and enhances midlevel mesocyclone compared to Z_BEC. It was also found that ML_BEC can significantly save the computational cost by reducing the need of running an even moderately sized ensemble.

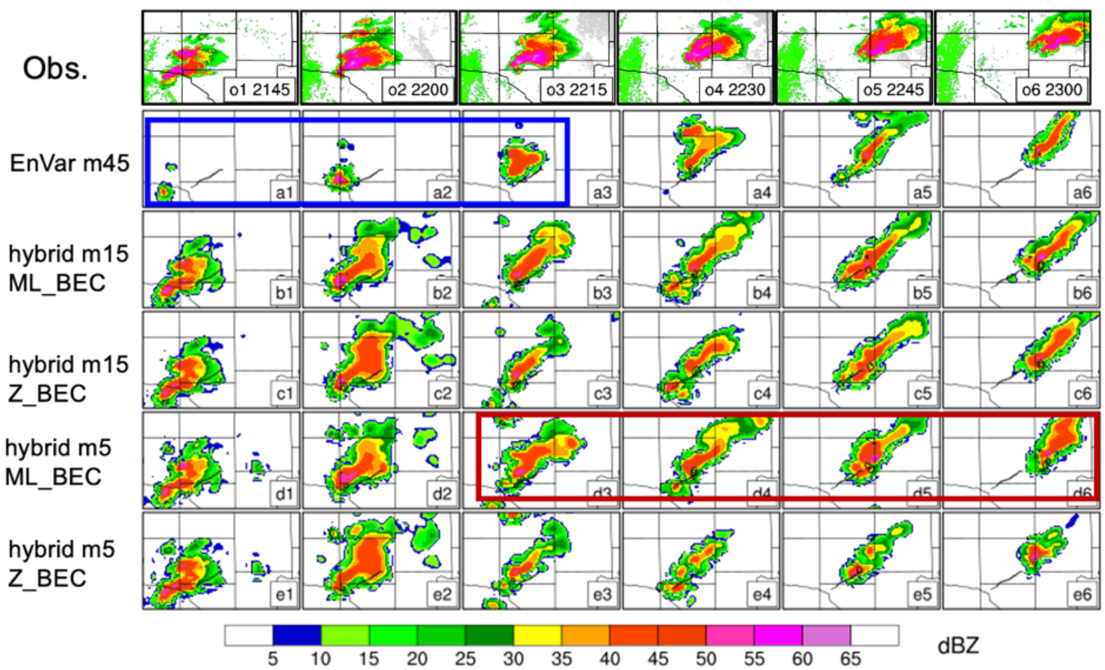


Figure 2-137: 2003 OKC tornadic supercell prediction from 5 data assimilation experiments (second to sixth rows) verified against the observations (first row). The second. To sixth rows are respectively initialized by the analysis produced by a pure EnVar using 45 member ensemble, hybrid using the new ML aided static covariance and 15 member ensemble, hybrid using the Wang and Wang (2021) static covariance and 15 member ensemble, hybrid using the new ML aided static covariance and 5 member ensemble, hybrid using the Wang and Wang (2021) static covariance and 5 member ensemble

CIWRO Theme: Mesoscale and Stormscale Modeling
CIWRO Contributors: Xuguang Wang, Aaron Johnson
Project Title: UFS R2O Phase I: Rapid Refresh Forecast System (RRFS) development and implementation
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and maturing the next-generation earth system models

The Advanced Baseline Imager (ABI) aboard the GOES-16 and GOES-17 satellites provides high-resolution observations of cloud structures that could be highly beneficial for convective-scale DA. However, only clear-air radiance observations are typically assimilated at operational centers due to a variety of problems associated with cloudy radiance data. As such, many questions remain about how to best assimilate all-sky radiance data, especially when using hybrid DA systems such as EnVar wherein a nonlinear observation operator can lead to cost function gradient imbalance and slow minimization. Here, we develop new methods for assimilating all-sky radiance observations in EnVar using the novel Rapid Refresh Forecasting System (RRFS) that utilizes the Finite-Volume Cubed-Sphere (FV3) model. We first modify the EnVar solver by directly including brightness temperature (T_b) as a state variable. This modification improves the balance of the cost function gradient and speeds up minimization. Including T_b as a state variable also improves the model fit to observations and increases forecast skill compared to utilizing a standard state vector configuration. We also evaluate the impact of assimilating ABI all-sky radiances in RRFS for a severe convective event in the central Great Plains. Assimilating the radiance observations results in better spin-up of a tornadic supercell (Fig. 1). These data also aid in suppressing spurious convection by reducing the snow hydrometeor content near the tropopause and weakening spurious anvil clouds. The all-sky radiance observations pair well with reflectivity observations that remove primarily liquid hydrometeors (i.e., rain) closer to the surface. Additionally, the benefits of assimilating the ABI observations continue into the forecast period, especially for localized convective events.

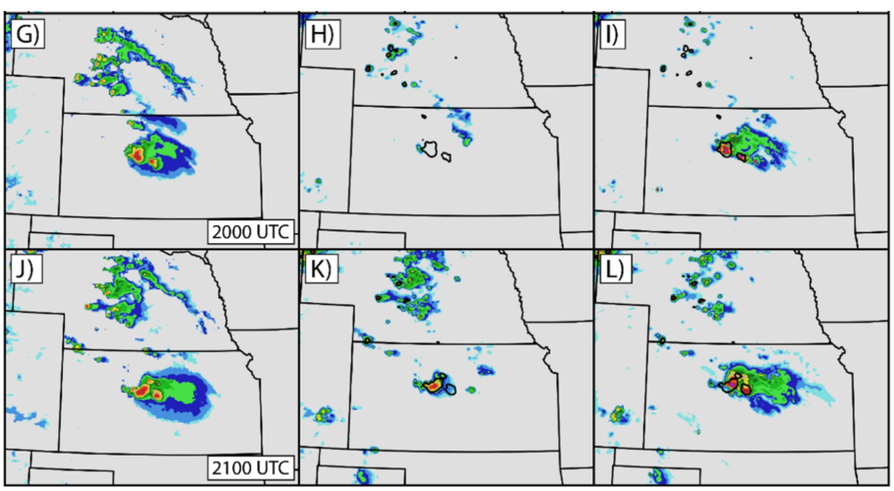


Figure 2-138: Observations and analyses of composite reflectivity (dBZ) for the tornadic supercell during each DA cycle between 2000 UTC and 2100 UTC 26 May. Shown are (g,j) observations; (h,k) analyses for the RADAR experiment; and (i,l) analyses for the RADAR+ABI experiment. Overlaid in solid black contours for the right two columns are observed composite reflectivity greater than 30 dBZ.

CIWRO Themes: Mesoscale and Stormscale Modeling, Forecast Applications Improvements
CIWRO Contributors: Aaron Johnson, Xuguang Wang, Andrew Shearer
Project Title: Development of hybrid static-ensemble background error covariance model for improved assimilation of all-sky ABI IR radiances in RRFSv2
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and maturing the next-generation earth system models

Despite the demonstrated benefits of convective scale data assimilation (DA) of the high space and time resolution all-sky radiances available from the advanced baseline imager (ABI), the maximum benefit of the radiance observations is not being realized due to limitations of the ensemble-based background error covariance (BEC) in certain situations. In particular, under-dispersion of the background forecast ensemble can result in situations where all, or most, ensemble members forecast a cloudy scene but the observation indicates clear air, and situations where all, or most, ensemble members forecast clear air but the observation indicates cloud, leading to reduced performance of ensemble DA methods. Work under this project has shown that ABI brightness temperatures (BTs) can be used to infer useful information about the vertical structure of thermodynamic (e.g., Figure 1) and cloud-microphysical (not shown) features by averaging ensemble covariances to model state variables over past samples in the same category of cloud altitude and precipitation presence. The cloud adaptive approach to calculating covariances between BT and model state variables is being used to improve additive inflation methods, which mitigate deficiencies in real-time ensemble-based estimates of BEC that occur in certain situations. Ultimately, the cloud adaptive approach will also be integrated into the development of hybrid ensemble-BEC models used for the assimilation of all-sky infrared radiances at convective scales in the NOAA regional modeling system. The work is supporting 1 GRA, and has been presented in 2 professional conference and workshop presentations, and in 1 professional conference poster.

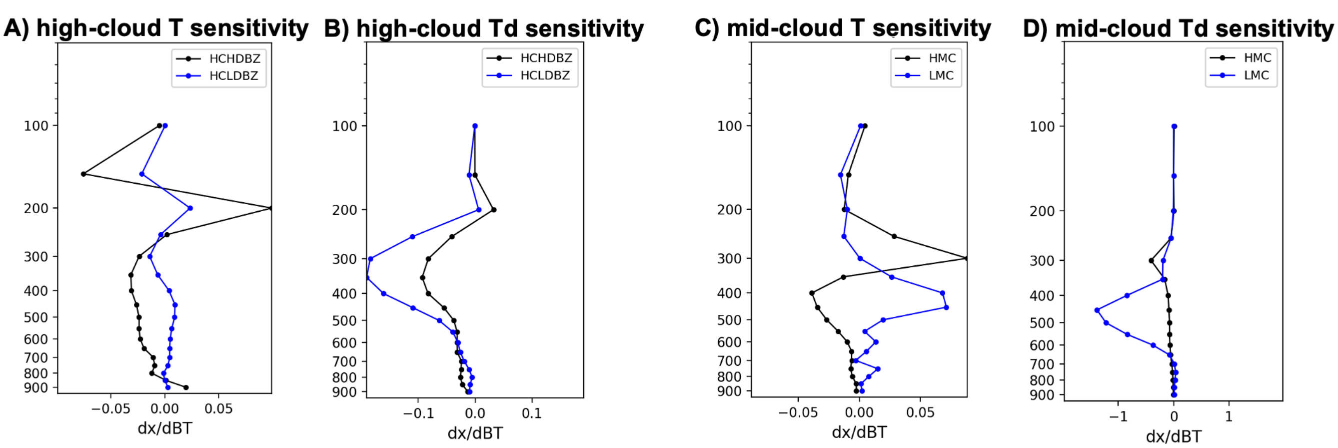


Figure 2-139: Sensitivity of temperature, T, and dewpoint, Td, model state variables to a unit change of 1K in channel 10 ABI brightness temperature, averaged over samples with (a) high clouds for T (precipitating high clouds in black and non-precipitating high clouds in blue), (b) as in (a) except for Td, (c) mid-level clouds for T (upper-mid-level clouds in black and lower-mid-level clouds in blue), and (d) as in (c) except for Td.

iii Forecast Application Improvements

Under the Forecast Application Improvements theme, CIWRO accelerates the transfer of research knowledge and skills between the academic and NOAA operational meteorological communities. This contributes to improve both the design and utilization of weather observing systems and improve weather analysis, prediction and warning products. One critical aspect of this progress is the enhancement of observation and analysis capabilities. By refining data collection and interpretation methods, meteorologists can better identify remotely sensed signatures of severe weather, classify precipitation types, and develop advanced data analysis tools. These efforts contribute to a deeper understanding of severe weather patterns, enabling more accurate assessments. Building on these observational advancements, research in prediction methods enhances forecast accuracy from hours to days in advance. Probabilistic guidance techniques help forecast thunderstorm hazards such as hail, tornadoes, lightning, damaging winds, and flooding rainfall. Additionally, efforts to improve predictions for winter weather and wildfires, as well as the rigorous verification of deterministic and probabilistic forecasts, ensure that meteorologists can provide reliable guidance for both routine and extreme weather events. For immediate threats, nowcasting and warning innovations refine the ability to detect and respond to severe weather in real time. Cutting-edge algorithms enhance the detection and short-term forecasting of hazardous conditions, including severe storms, flooding, winter weather, and aviation threats. Integrating Probabilistic Hazard Information (PHI) with the WoFS further strengthens short-term guidance, equipping forecasters with high-confidence decision-support tools. Bridging the gap between research and operational deployment, testbed and real-time experiments play a crucial role in refining forecasting capabilities. Programs such as the Spring Forecast Experiment (SFE) and the Experimental Warning Program (EWP) provide opportunities for researchers and forecasters to collaboratively evaluate new methodologies, ensuring that scientific advancements translate into practical, actionable improvements for operational meteorology. To fully realize the benefits of these scientific advancements, training initiatives empower meteorologists with the knowledge and skills needed to effectively implement new forecasting tools and techniques. Courses such as the long-running Radar and Applications training, warning operations programs, and specialized instruction for NWS information technology staff ensure that forecasters remain proficient in evolving meteorological technologies. Webinars and leadership training further support the development of a knowledgeable and adaptive forecasting workforce.

Through these interconnected efforts, CIWRO transforms research into meaningful forecasting improvements, equipping forecasters with innovative tools to enhance public safety and decision-making. By harnessing state-of-the-art science and technology, meteorologists can provide increasingly accurate and actionable weather information to emergency planners, decision-makers, and the public, ultimately improving preparedness and resilience against severe weather events.

CIWRO Themes: Forecast Application Improvements, Weather Radar and Observations
CIWRO Contributor: John Krause
Project Title: Investigating hailstorm updrafts and nowcasting hail size using radar-based updraft detection
Relevance to NOAA: This project supports the NOAA mission by Developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

Using the hotspot updraft detection method, several radar derived variables were (230 reduced to 34) computed and used to forecast hail size. A large hail size dataset (size, location, time) was constructed to train a random forest and this dataset was time corrected so that accurate hail fall was assured. With accurate times of hail fall, we were able to forecast the categorical size of hail (no, small, medium, large, giant) from storms up to 20 min in advance using a random forest. This project led to 2 conference presentations and 1 journal article (Klaus and Krause, 2024).

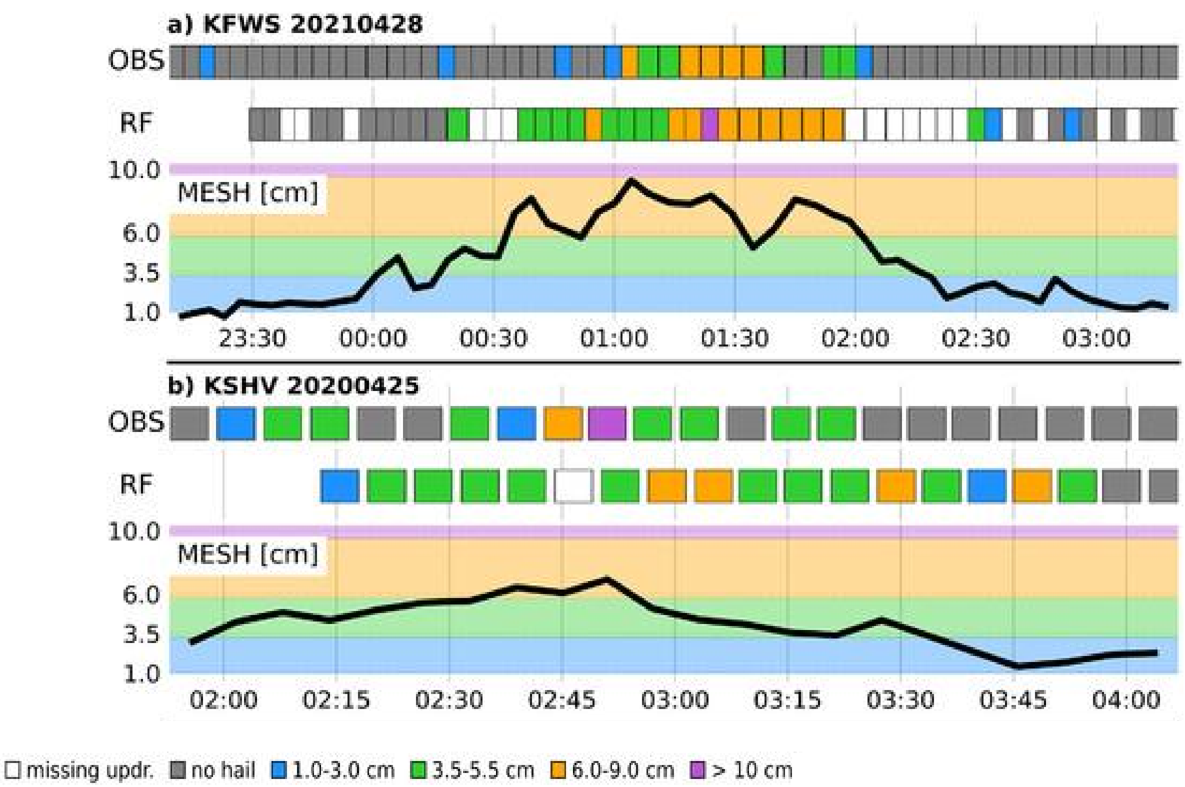


Figure 2-140: Two example nowcasts of the random forest (RF) model compared to hail observations (OBS) and MESH. OBS on the first line and time-aligned model (RF) 20-min forecasts of hail size on the second line, and colors indicate the hail size category. (Weather and Forecasting 39, 12; 10.1175/WAF-D-23-0227.1)

CIWRO Themes: Forecast Application Improvements, Weather Radar and Observations
CIWRO Contributor: Jacob Segall
Project Title: Improving tornadogenesis nowcasting via tracking and analysis of size sorting signatures
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions.

This project consists of three main objectives: 1) the development of an automated algorithm for identifying and tracking hydrometeor size sorting signatures, 2) comparing the performance of our hydrometeor size sorting algorithm with past studies, and 3) using the newly developed algorithm to elucidate relationships between size sorting signatures and the convective environment for use in the real-time tornado identification. The work from Objectives 1 and 2 reveals the new methodology is capable of reliably providing forecasters with information regarding size sorting signatures in supercell thunderstorms, which is detailed in Segall et al. (2025). Hence, this tool has the potential to lessen the workload on forecasters and, more broadly, could lead to longer warning lead times and more confident warnings in the future. The ongoing work in Objective 3 may help relate hydrometer size sorting to additional relevant near-storm environmental differences between tornadic and non-tornadic storms. Current outcomes from this project include five conference presentations and a journal article in review. External partners involved in this project include the U.S. Naval Academy, the National Center for Atmospheric Research, and NWS/ROC.

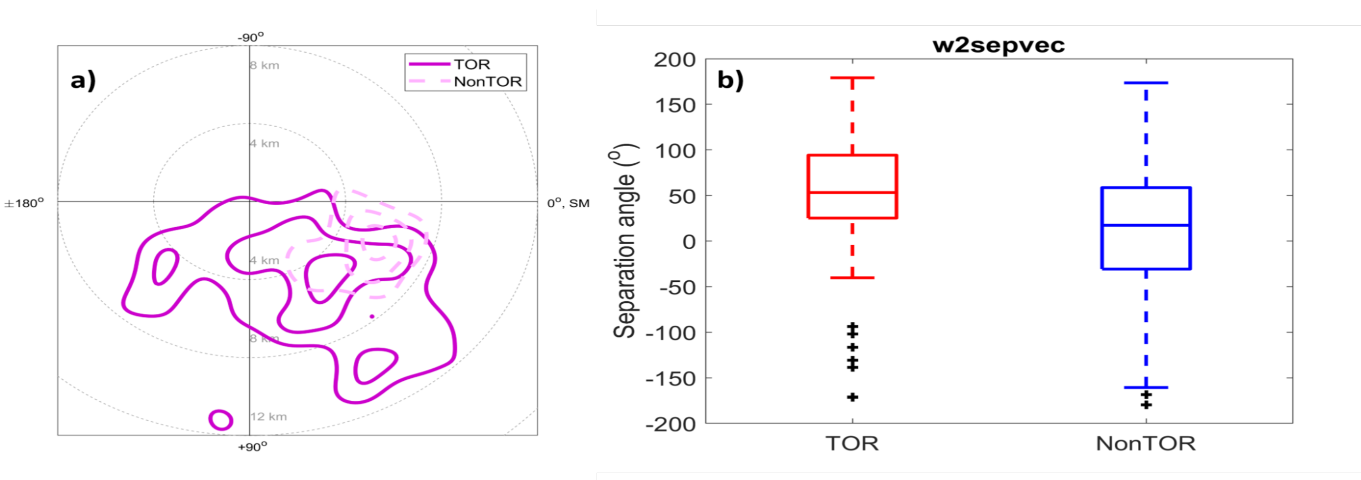


Figure 2-141: a) Kernel density estimate for the automated algorithm's differential reflectivity-specific differential phase (Z_{DR}-K_{DP}) separation vector orientation angle output for tornadic (solid contours) and non-tornadic (dashed contours) cases and (b) boxplots for the distributions Z_{DR}-K_{DP} separation vector orientation angles for tornadic (red) and non-tornadic (blue) cases from Segall et al. (2025).

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Tyler Bell, Joshua Gebauer
Project Title: Tropospheric remote profiling via optimal estimation
Relevance to NOAA: This project supports the NOAA mission by optimizing platform agnostic data and information, improving observation quality and stewardship, and developing next generation observational capabilities.

This is a joint project with scientists from NOAA Global System Laboratory to continue to develop a physical based optimal estimation retrieval for thermodynamic profiling from ground based remote profilers. This retrieval, referred to as TROPoe, is an extension of original AERIoe retrieval. That retrieval was ported to Python and containerized to increase the accessibility of the retrieval for the general community. Additionally, the retrieval was updated substantially to increase its performance and more generalized for the large array of thermodynamic remote profilers that exist. This software is an important component for developing next generation observation capabilities, as it unlocks many radiation based observations of the atmosphere for operational use. During this phase of the project, we have released the software, and it is being transitioned to operations at ARM DOE.

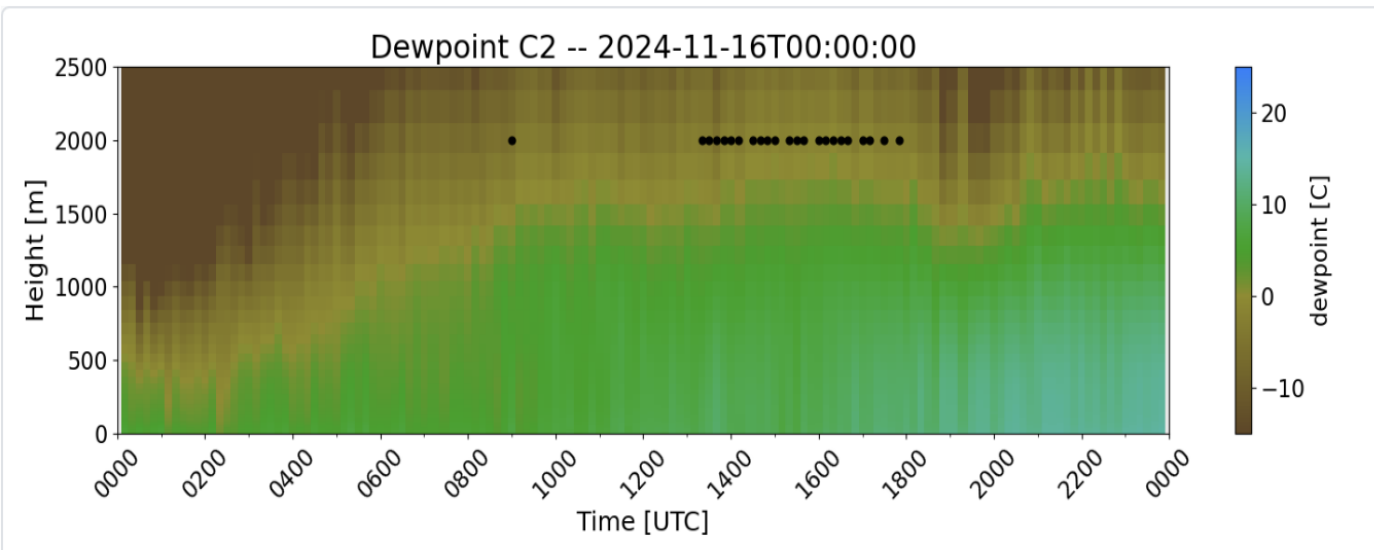


Figure 2-142: Example of retrieved dewpoint profiles using TROPoe from the CLAMPS 2 Atmospheric Emitted Radiance Interferometer (AERI) at the OU Kessler Atmospheric and Ecological Field Station on 16 November 2024. Black dots indicate the cloud based height

CIWRO Themes: Forecast Application Improvements, Weather Radar and Observations
CIWRO Contributor: David Harrison
Project Title: The creation of a new lightning data webpage
Relevance to NOAA: This project supports the NOAA mission by optimizing platform-agnostic data and information.

This project developed a new interactive webpage to display lightning data for the CONUS in planar view and in point-based time series and heat maps. Work is ongoing to further update the interface and capabilities of the webpage to additionally display severe and fire weather records for CONUS, Alaska, Hawaii, Puerto Rico, and American Samoa. This webpage is currently available to the public on the SPC website, and we have received mostly positive feedback from both the NWS and members of the public. Tangible outcomes from this project include 1 publicly available webpage and 1 conference presentation. This project was performed in collaboration with NCEP/SPC, NWS/AFS, and NWSFO-Medford, OR.

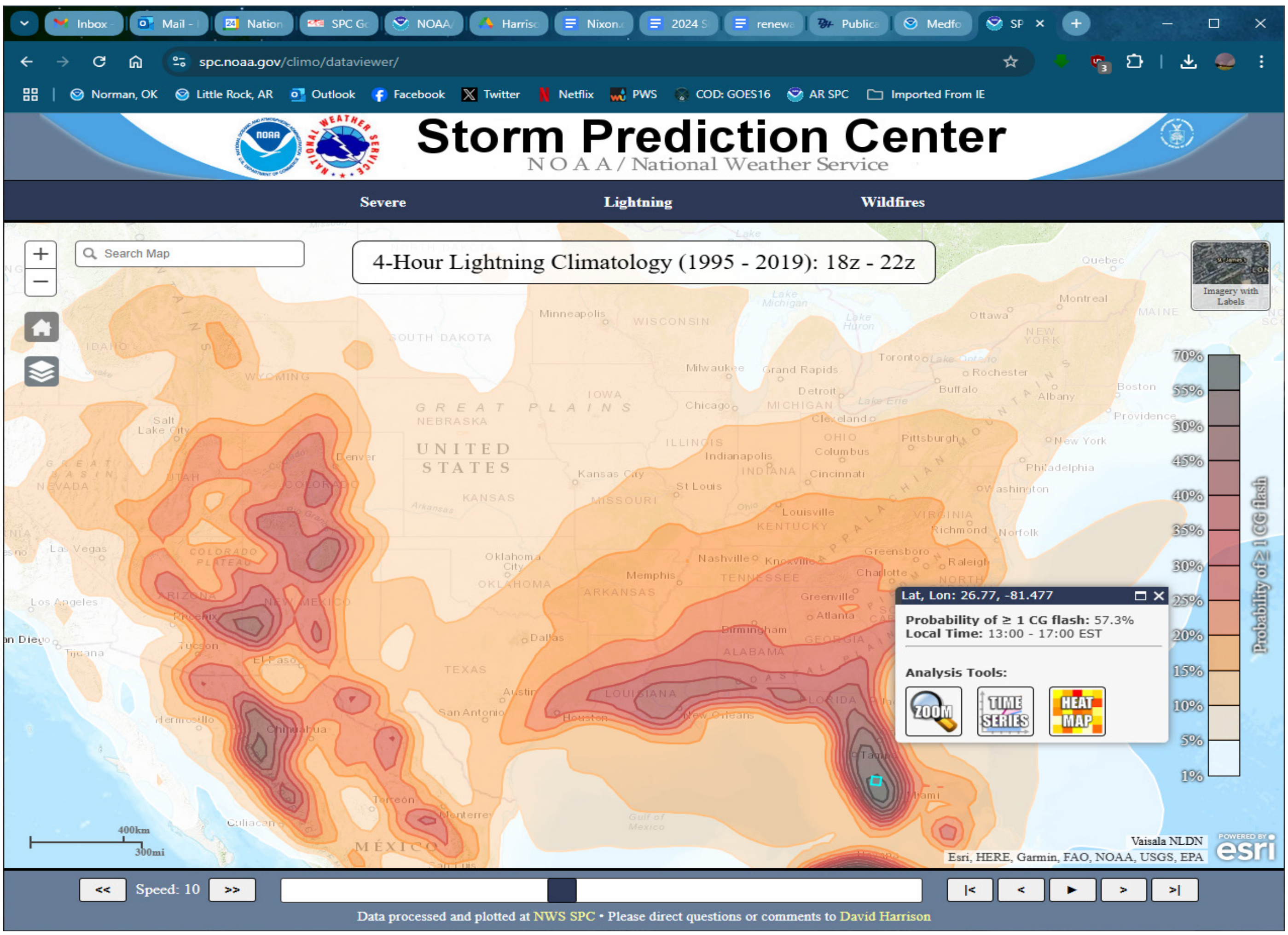


Figure 2-143: Screenshot of the new public lightning data webpage (https://www.spc.noaa.gov/climo/dataviewer/).

CIWRO Themes: Forecast Application Improvements, Weather Radar and Observations, Sub-seasonal-to-Seasonal Prediction for Extreme Weather
CIWRO Contributors: Wenjun Cui, Kiel Ortega
Project Title: Developing severe event descriptions based on large radar data and machine learning
Relevance to NOAA: This project supports the NOAA mission by creating/improving a trusted analysis of record for model verification/nowcasting.

The project focuses on two primary objectives: 1) developing machine learning algorithms to predict the probability of storm objects producing severe events and 2) reconstructing severe weather event databases to identify historical trends and patterns. Machine learning models were developed and applied to storm cluster data derived from the Multi-Year Reanalysis of Remotely Sensed Storms (MYRORSS) radar dataset developed at NSSL. The models then generated a new, multi-year severe event database that mitigates underreporting biases associated with human-based methods and observational heterogeneities. These models have demonstrated superior performance compared to NOAA's operational tools in identifying tornadic storms and offer potential for integration into real-time forecasting workflows to improve severe weather guidance. Outcomes include two presentations and a lead-author publication in review detailing the machine learning-derived tornado analysis (Cui et al. 2025).

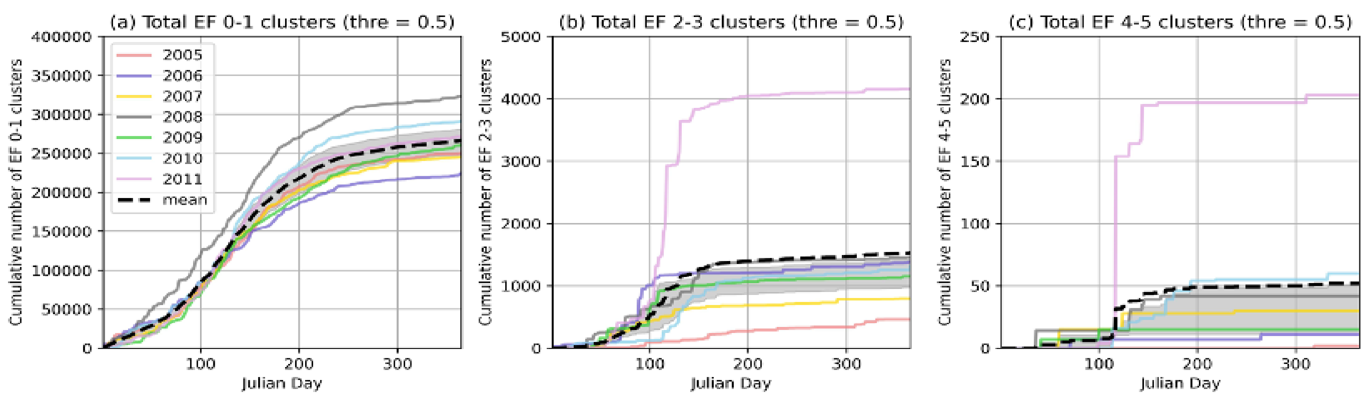


Figure 2-144: Estimated cumulative number of storm clusters associated with (a) Enhanced Fujita-scale (EF) 0–1, (b) EF 2–3, and (c) EF 4–5 tornadoes as a function of Julian day using the 0.5 probability threshold value based on machine learning models from Cui et al. (2025).

CIWRO Themes: Forecast Application Improvements, Weather Radar and Observations
CIWRO Contributors: Joseph Picca, David Harrison
Project Title: The creation of a new sounding database webpage
Relevance to NOAA: This project supports the NOAA mission by optimizing platform-agnostic data and information.

In this project a significant update was made to the public SPC sounding webpage. The project redesigned the appearance and functionality of the webpage, allowing users to customize and more robustly investigate the data presented. This updated design enables users in the weather enterprise to gain further insight into observed upper-air sounding information by allowing deeper contextual analysis. Subjective feedback from NWS users has been positive since the deployment, highlighting the functionality and visualizations on the page. Tangible outcomes from this project include 1 publicly available webpage. This project was performed in collaboration with NCEP/SPC.

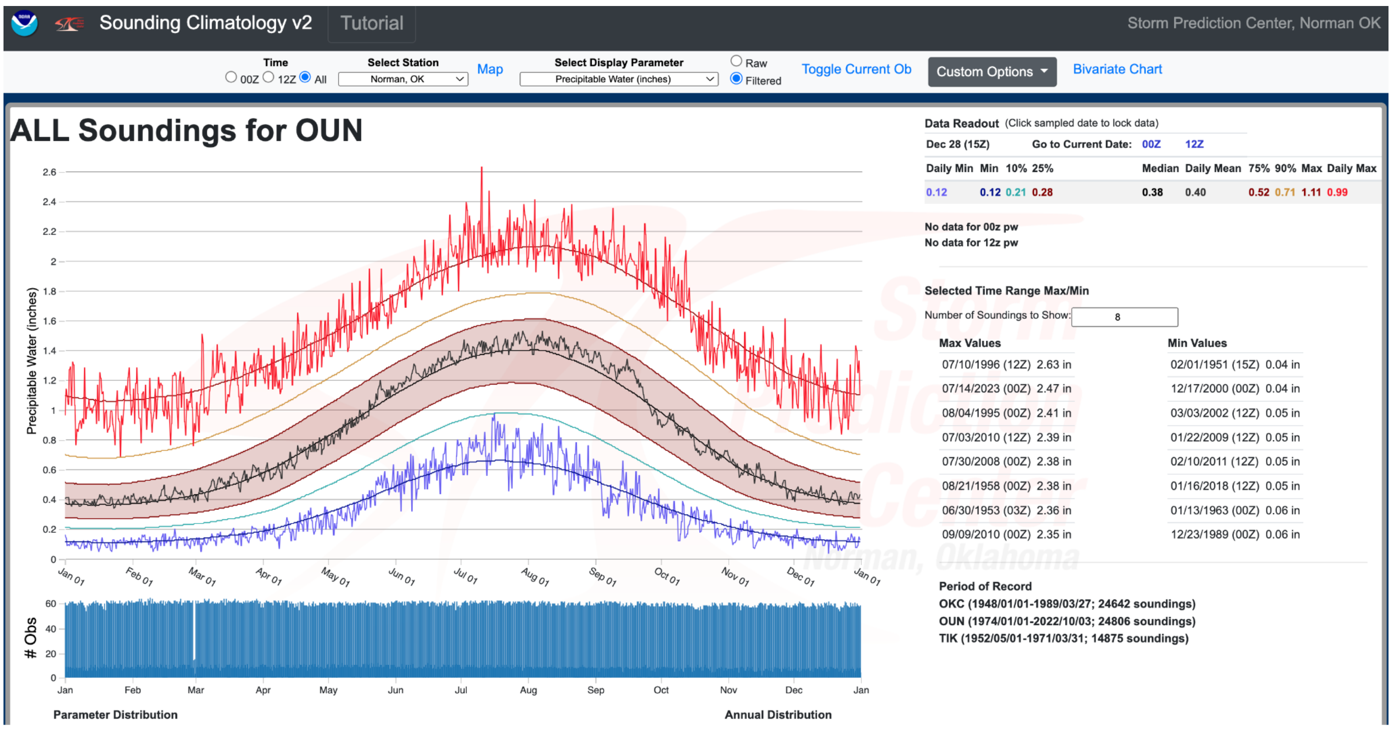


Figure 2-145: Screenshot of the new public sounding webpage (https://www.spc.noaa.gov/exper/soundingclimov2/), in which users can filter and customize their view of historic data.

CIWRO Themes: Forecast Application Improvements, Subseasonal-to-Seasonal Prediction for Extreme Weather Systems
CIWRO Contributors: Daniel Tripp, Heather Reeves, Adam Werkema
Project Title: The creation of a gridded analysis of record of freezing rain accumulation
Relevance to NOAA: This project supports the NOAA mission by creating/improving a trusted analysis of record for model verification/nowcasting.

In this project a new decision-support capability for MRMS, the Freezing Rain Accumulation National Analysis (FRANA), is created. This product is a gridded, CONUS-wide analysis of ice accumulation that has a 1-h cadence and 1-km horizontal resolution. The product includes both accumulating and trace ice as well as radial and flat-ice accumulation rates. It is intended for nowcasting, post-event verification, and seasonal ice accumulations (Tripp et al. 2025). Statistical analysis of a three-year retrospective of FRANA shows that it provides skill both for the total footprint and for the accumulation amount. FRANA is available to NWS forecasters in real time as an experimental product and has been in use for 2 winter seasons and has been evaluated in the WPC's winter-weather experiment testbed. It is also being used to quantify seasonal ice accumulations and in support of FEMA federal disaster declarations. Tangible outcomes from this project include 1 formal journal article, 3 conference presentations, and 1 algorithm ready for transition to NWS operations. External partners involved in this project include NWS Central Region Headquarters, NCEP/WPC, and NWS/AFS.

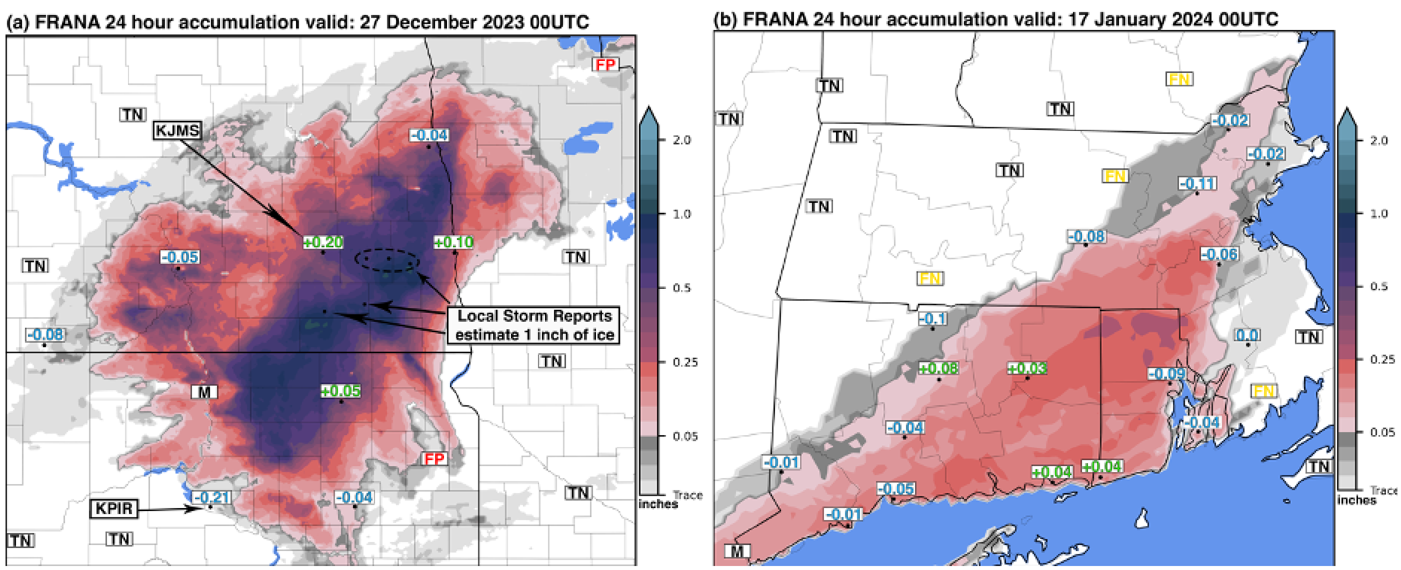


Figure 2-146: Examples of 24-h ice accumulations from FRANA output as it compares to ASOS observations (FP = false positive, TN = true negative, M=missing data) at (a) 0000 UTC 27 December 2023 and (b) 0000 UTC 17 January 2024.

CIWRO Themes: Forecast Application Improvements
CIWRO Contributor: Andrew Wade
Project Title: Refining the definition, identification, and forecasting of derechos
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions, and improving continuous engagement with partners.

Derechos pose a forecast and communication challenge for the NWS SPC. Stakeholders often ask whether a particular wind event was or could be a derecho, but many inconsistent sets of published criteria are in use (Squitieri et al. 2023a, b). This long-running project first created an algorithm to track MCSs in WSR-88D mosaic reflectivity, based in part on Haberlie and Ashley (2018), and match wind reports to them. This yielded a dataset of thousands of MCSs 2000–2023 (Wade et al. 2023). Numerous combinations of possible derecho criteria were tested on MCSs that produced significant severe wind. This work led SPC to propose a refined definition and set of criteria emphasizing widespread, verifiable significant severe wind (Squitieri 2024, Squitieri et al. 2025). A set of 78 derechos meeting these criteria is being used to update the description of derechos (Squitieri 2024), identify associated synoptic regimes (Wade et al. 2024), explore forecast parameters, and quantify SPC forecast performance. Four conference presentations and four AMS journal articles—two review articles, two on these findings—have resulted thus far. We mentored three OU capstone students who will add a fifth conference presentation. A near-real-time adaptation of the MCS/derecho tracking algorithm and proposed criteria now provides awareness for SPC forecasters, as well as consistent information for stakeholders who want to know if a derecho has occurred. Internal discussion groups, training, and meetings with forecasters and management have facilitated O2R/R2O transfer in this project.

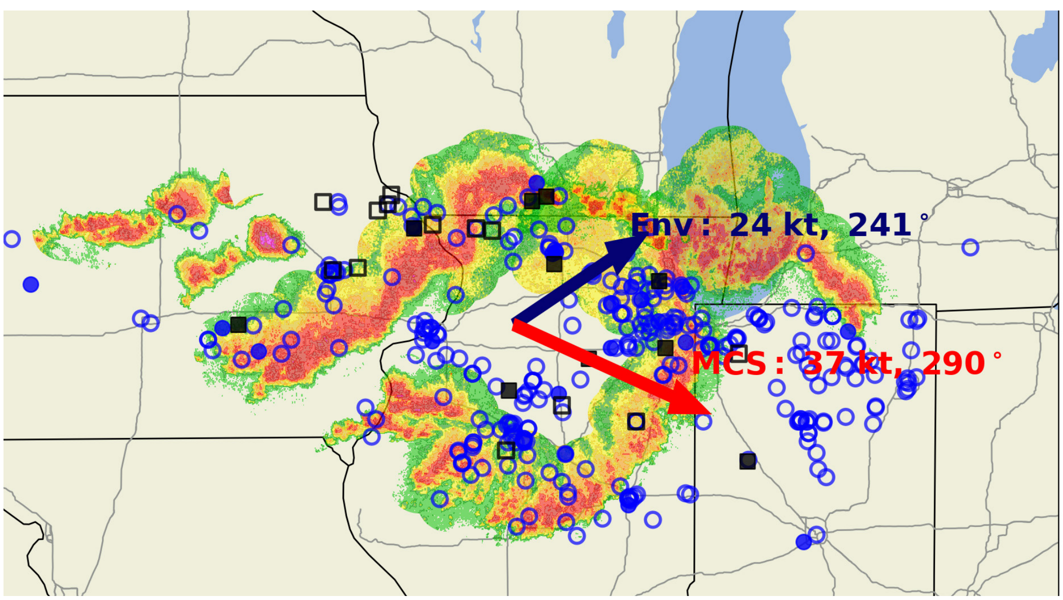


Figure 2-147: An example of a real-time summary graphic distributed by SPC to stakeholders, with mosaic reflectivity associated with the tracked MCS (shaded) and preliminary wind reports matched to the MCS (circles and squares) for the 15 July 2024 Chicago-area derecho event.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributor: Kelton Halbert
Project Title: Standalone library for computing thermodynamic and kinematic indices
Relevance to NOAA: This project supports the NOAA mission by creating/improving a trusted analysis of record for model verification/nowcasting and optimizing platform-agnostic data and information

Developed a standalone library for computing thermodynamic and kinematic indices based on atmospheric sounding profiles in the support of an upgraded sounding analysis and visualization toolkit at SPC. This library is unique in that it is completely generalized for multiple application types - whether analyzing single sounding sources (radiosondes, point-forecast soundings), gridded datasets (mesoanalysis or model post processing), or analyzing an ensemble of datasets. The library is written in C++, but provides a fully implemented C-api wrapper, which makes it possible to embed these routines into existing C and FORTRAN software. This makes the library a valuable tool for both research and prototyping using Python, since it is the common data science language of choice. More importantly, making it a compiled library accessible to Python means that datasets can be processed significantly faster than in pure Python. The goal of this project was to provide a single, tested, accurate, and performance optimized source library that can be leveraged by any of the operational and science-based projects within SPC, without having duplicate/differing implementations. The library was implemented operationally as part of the significant upgrade to existing NOAA open-source operational tools (NSHARP and SHARPpy) used by the SPC and the Aviation Weather Center. This work resulted in 1 conference presentation.

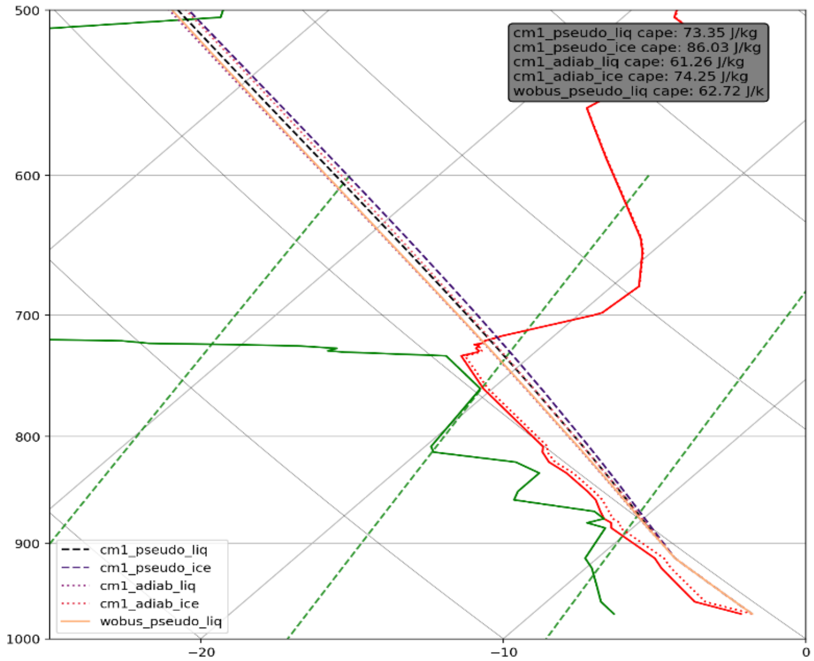


Figure 2-148: Example sounding profiles (moist adiabats) and thermodynamic parameters calculated using functions from the new library.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Andrew Wade, Jacob Vancil
Project Title: Using practically perfect hindcasts to identify significant severe outbreaks and their environments
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions.

Past studies of significant severe environments have typically evaluated point profiles near a target storm, stratifying the environments by the maximum intensity within some spatiotemporal window. But this says little about whether widespread or isolated significant severe impacts should be expected. This project created practically perfect hindcasts (PPHs; Hitchens et al. 2013) of each significant severe hazard for all 12–12 UTC convective days 2007–2021 (inclusive) and defined 'outbreaks' as the top decile of gridpoint-maximum PPH values for each hazard. This top decile of significant tornado days—four days a year on average, only 2.5% of all U.S. tornado days—accounted for 75% of direct tornado fatalities, 65% of direct tornado injuries, and 50% of tornado property damage over the analysis period. Environmental fields centered on each event's maximum PPH were drawn from the SPC mesoanalysis (Bothwell et al. 2002) and averaged, creating both 2D composite fields (below) and vertical profiles/hodographs for all significant severe, isolated events (those occurring in a single grid cell), and outbreaks. Kinematic parameters like 0–6-km bulk shear and 0–1-km storm-relative helicity proved highly useful in distinguishing EF2+ tornado outbreaks from isolated EF2+. The outbreak composite hodograph was larger than the isolated composite throughout a deep layer from near the surface to beyond 6 km above ground. Thermodynamic parameters like mixed-layer CAPE showed little difference. These findings were presented at an AMS SLS conference.

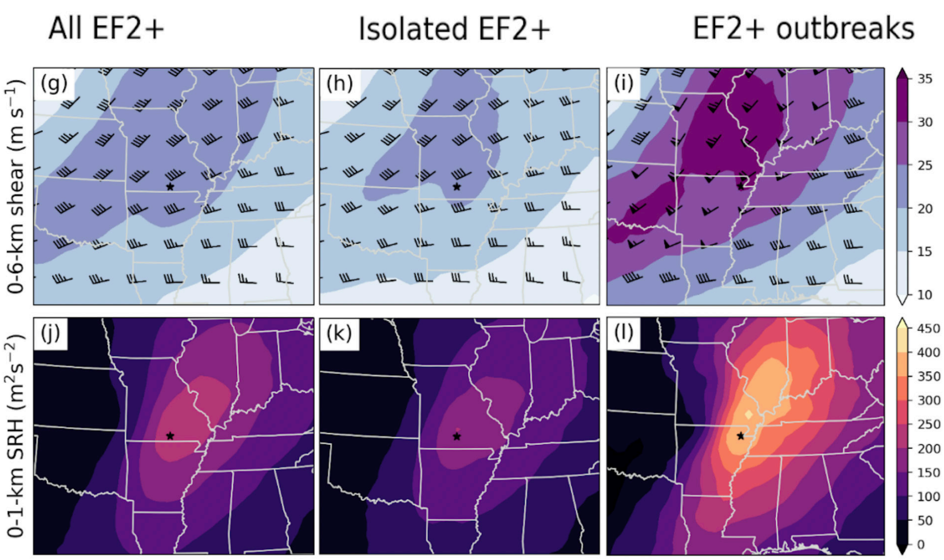


Figure 2-149: Composite, (g–i) 0–6-km bulk shear, (j–l) 0–1-km storm-relative helicity in (left to right) all significant tornado events, isolated significant tornado events, and significant tornado outbreaks. Barbs in panels (g–i) represent 10 kt; pennants represent 50 kt. [Adapted from Wade et al. (2022). Not shown (a–c) mixed-layer CAPE, and (d–f) mixed-layer LCL].

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Heather Reeves, Daniel Tripp, Andrew Rosenow
Project Title: Building decision-support tools for winter precipitation type nowcasting/forecasting using spectral-bin microphysics
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events

This project focused on building new decision-support tools for winter precipitation-type (ptype) utilizing the spectral-bin classifier (SBC; Reeves et al. 2022, 2023). The SBC is a stripped-down bin microphysics scheme that can provide information on hydrometeor phase throughout a vertical profile and at the surface for various particle sizes. This product has been running inside of MRMS as a precipitation type analysis and is able to discriminate mixes (e.g. Rain/ice pellet, rain/snow, etc.) and drizzle/freezing drizzle. Decision-support tools for aviation applications and general forecasting have been created to explore the best ways to display the output. The SBC is currently being utilized as an input for other MRMS algorithms and has been evaluated in the WPC's winter-weather experiment testbed. Tangible outcomes from this project include 2 formal journal articles, 4 conference presentations and 1 algorithm ready for transition to NWS operations External partners involved in this project are NCEP/WPC and the FAA.

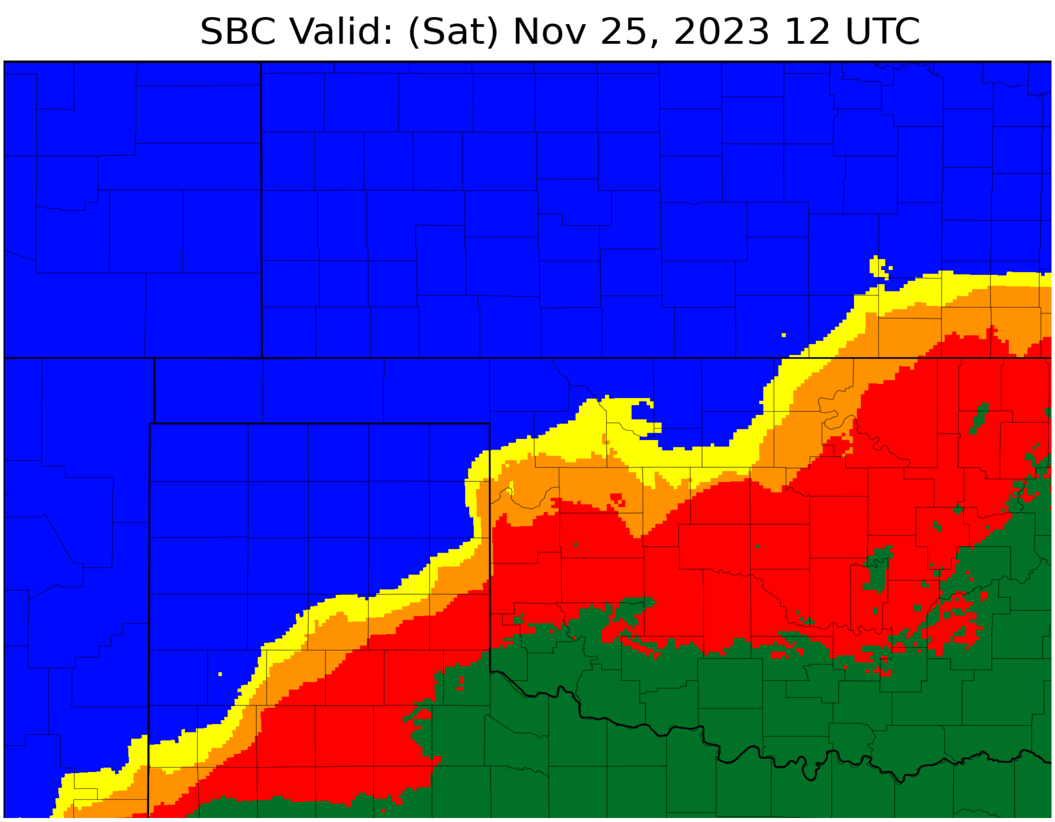


Figure 2-150: Example of the SBC precipitation type for a mixed-phase precipitation event on 25 November 2023 at 11 UTC. Green = Rain; Red = Freezing Rain; Orange = Freezing Rain/Ice pellet; Yellow = Ice pellet; Blue = Snow.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributor: Jorge Duarte
Project Title: Machine learning for impact-based flash flood warnings - Large-language model-based classification of flash flood impacts across the United States
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events

The NWS has transitioned their warning paradigm to an impact-based format known as impact-based warnings (IBW). Due to this, there is an inherent need for developing novel impact-based decision support services (IDSS) which can aid forecasters in assessing the potential consequences of forecasted hazards, for the issuance of IBWs. In order to enable the development of said products for flash flood warnings, a systematic approach using Large Language Models (LLMs) has been used to classify historical local storm reports (LSRs) into impact classes using the Flash Flood Severity Index (FFSI). This unprecedented dataset has been successfully used to prototype machine learning models based on compound transformer architectures for forecasting flash flood impact severity. Tangible outcomes of this project include two conference presentations, one PhD dissertation, and one journal article.

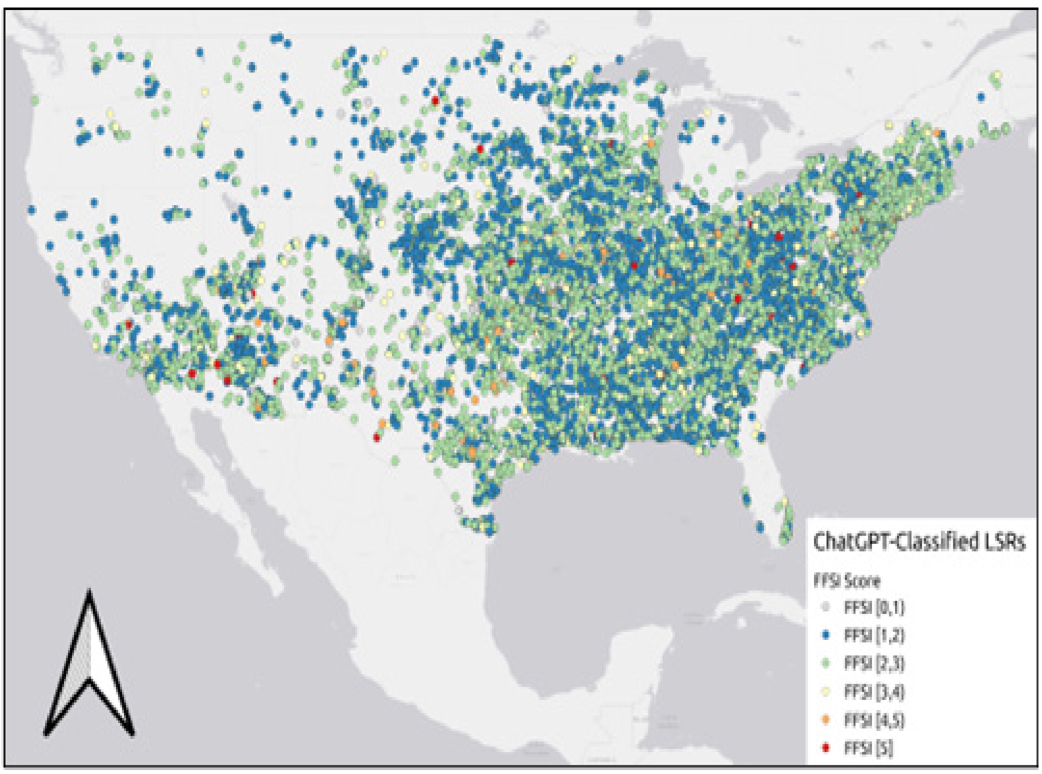


Figure 2-151: Map showing the geographical distribution of 2,329 GPT-classified Flash Flood LSRs over the United States. Each report has been classified into a FFSI class, based on their FFSI score derived from joint probability distributions assigned by the LLM.

CIWRO Themes: Forecast Application Improvements, Weather Radar and Observations
CIWRO Contributors: Heather Reeves
Project Title: Assessments of 18-dBZ echo top height for aviation decision making
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and developing reliable probabilistic guidance products.

The accuracy and uncertainty of radar echo-top heights estimated by ground-based radars remain largely unknown despite their critical importance for applications ranging from aviation weather forecasting to severe weather diagnosis. A comparison of the MRMS diagnosed 18-dBZ echo top height against space-based radar on board the NASA–JAXA Global Precipitation Measurement satellite platform shows there is no major bias between the two products. However, an annual cycle of differences is found, driven by an underestimation of the stratiform cloud echo-top heights and an overestimation of the convective ones. The investigation of the systematic biases for different radar volume coverage patterns (VCP) shows that scanning strategies with fewer tilts and greater voids as VCP 21/121/221 contribute to overestimations observed for high MRMS tops. Additional efforts quantify the manner in which mosaics of 18-dBZ echo top are produced and how these impact decision points in the aviation realm. These results indicate that different techniques can profoundly impact convective SIGMETs and aviation-specific forecasts of convection. Tangible outcomes stemming from this research include 1 journal article and 2 conference presentations. External partners of this research include the FAA and NCEP/AWC.

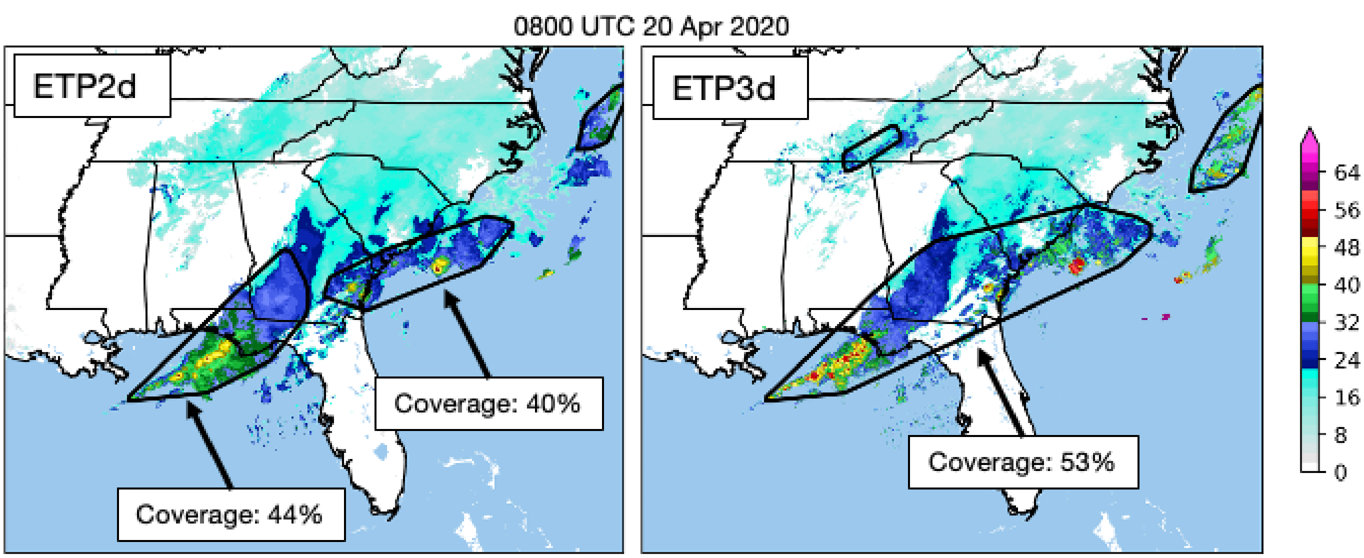


Figure 2-152: Convective avoidance polygons produced using 2 different versions of 18 dbZ echo top. The percent coverage in each polygon is indicated.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Ben Schenkel, Thea Sandmæl, Kayla Wheeler, Dzuy Nguyen, Ben Kassel, Marcus Ake, Zachary Fruits, Isaiah Schick
Project Title: Increasing our understanding of tropical cyclone tornado occurrence and evaluating their associated forecast skill
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

This project has two foci: 1) basic research identifying the factors driving variability in the number of tornadoes among tropical cyclones with similar characteristics and 2) applied research quantifying tropical cyclone tornado warning skill and the utility of products used in making these short-fused forecasts. The first part of this project has focused on investigating the characteristics of the tropical cyclone and its synoptic-scale environment in driving tornado variability. This work, thus far, has found that increasing synoptic-scale baroclinity is associated with greater numbers of tornadoes, especially strong ones, that become more strongly localized in the northeast quadrant of the tropical cyclone (Schenkel et al. 2020, 2021). Additional work has shown that more tornadoes occur farther from those tropical cyclones with broader wind fields (Paredes et al. 2021). The second portion of this work entails developing the first description of tropical cyclone tornado warning forecast skill. This work has shown substantial variability in forecast skill among tropical cyclones with no clear driver of this variability. Furthermore, this work has shown that radar-derived products (e.g., azimuthal shear) have more utility than lightning for identifying tornadic storms (Schenkel et al. 2023). Tangible outcomes from this project include 4 formal journal articles, 12 conference presentations, 5 National Weather Center REU students mentored, 1 M.S. degree completed, 9 SoM undergrads mentored, 2 SoM senior capstone groups mentored, and 1 funded NSF proposal. External partners involved in this project include NWS/SPC, OAR/NSSL, and OU/SoM.

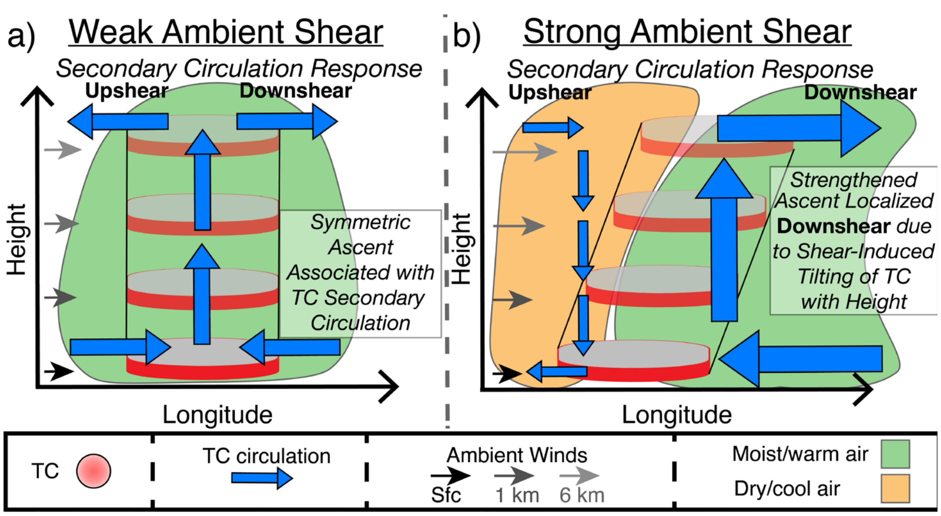


Figure 2-153: Schematic showing response of tropic cyclones to weak (a) versus strong (b) vertical wind shear as shown in vertical cross sections of the cyclone secondary circulation response based on current and prior work as shown in Schenkel et al. (2020).

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Jake Vancil
Project Title: Conditional intensity forecasting advancement
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

This project conducted analysis and verification of internally-issued SPC conditional intensity forecasts to measure the skill and performance of this new forecast framework. This work created programs to verify the daily and accumulated performance of these experimental forecasts. Given the conditional nature of these forecasts, traditional probabilistic verification methods were not feasible. Conditional intensity forecasts were instead broken down into multiple conditional intensity groups depending on the drawn forecast probabilities. A ratio of severe storm reports to significant severe storm reports were then calculated for each intensity group to provide forecast verification metrics. Intensity group ratios were accumulated as needed to provide long-term forecast performance. The daily and accumulated performance metrics, as well as forecaster drawn forecasts, were displayed to SPC forecasters via an internal webpage. Tangible outcomes from this project include 1 internal SPC webpage, 3 conference presentations, and 3 extended abstracts. This project was performed in collaboration with NCEP/SPC.

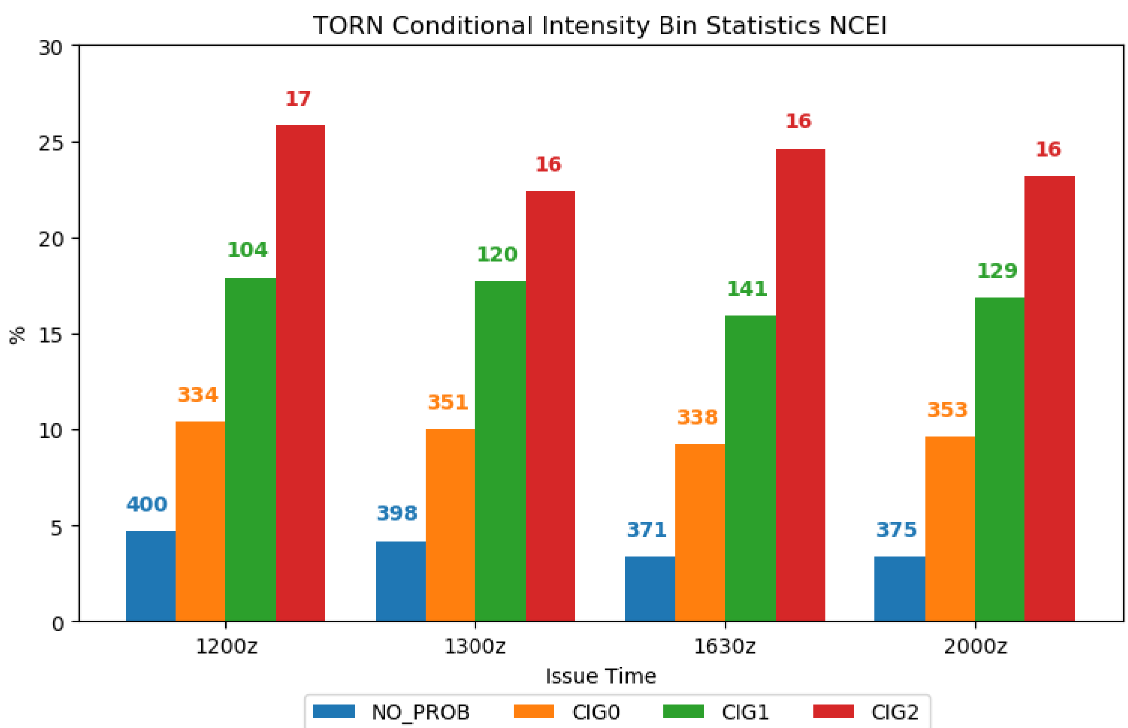


Figure 2-154: Bar chart showing the performance of internally issued SPC conditional intensity tornado forecasts by forecast issuance time (1200Z, 1300Z, 1630Z, 2000Z) from 1 Nov 2021 – 31 July 2024. Each colored bar represents a conditional intensity group (CIG) and the number of times each group was forecast during the analysis period.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributor: Kimberly Hoogewind
Project Title: Developing calibrated convective guidance from GEFSv12
Relevance to NOAA: This project supports the NOAA mission by developing reliable probabilistic guidance products.

Under the Unified Forecast System (UFS) framework, several legacy mesoscale operational forecast systems, such as the Short-range Ensemble Forecast (SREF), are slated for retirement. It is intended that the operational Global Ensemble Forecast System (GEFS) will serve as a replacement for the SREF. To provide evidence to potentially accelerate the retirement of the SREF while still meeting the needs of stakeholders, this project developed forecast thunderstorm and severe thunderstorm probabilities, utilizing the 20-years of GEFS hindcasts for training, to evaluate whether these known issues could be corrected through statistical calibration. The experimental products were evaluated, alongside their analogous SREF counterparts, during two years of the HWT-Spring Forecasting Experiment (SFE). It was demonstrated through both subjective evaluations and objective forecast verification that statistically calibrated GEFS forecast probabilities were on par with, or even better, than the SREF. The promising results have bolstered stakeholder confidence that the GEFS may supersede the SREF for convective guidance purposes. Tangible outcomes include 2 HWT-SFE evaluations, creation of a web viewer for pseudo-operational, 1 conference presentation, and 1 presentation to the NOAA short-range weather and convection-allowing modeling working group. External partners involved in this project included NWS/SPC and NCEP/EMC.

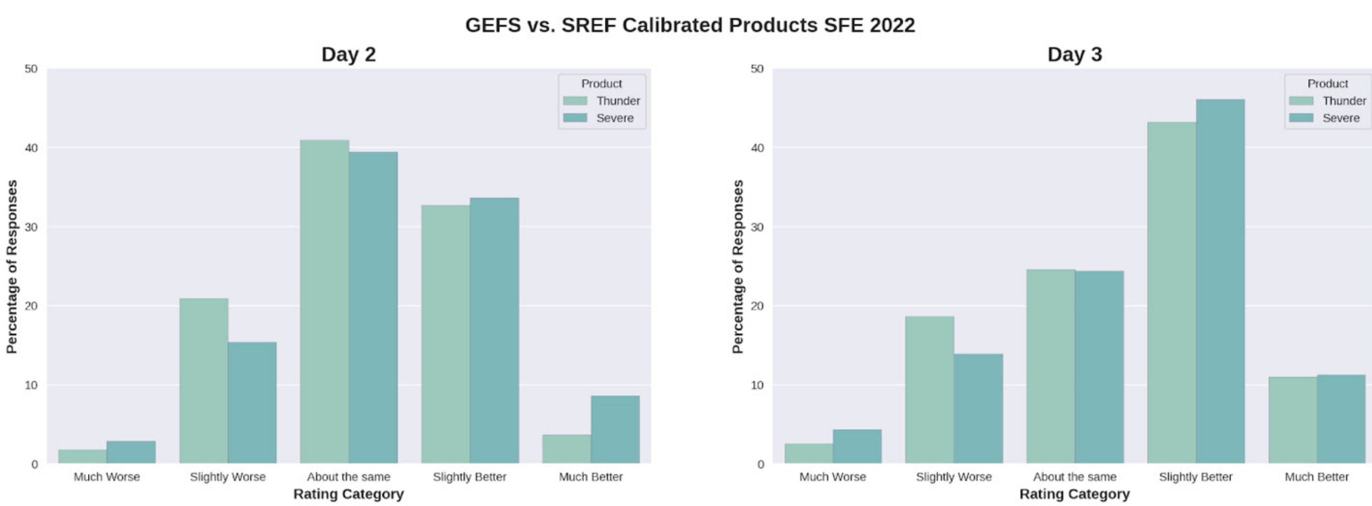


Figure 2-155: Subjective evaluations rating calibrated thunderstorm and severe thunderstorm probabilistic guidance produced from GEFS relative to SREF. Results demonstrate that >77% and >81% of participants rated GEFS calibrated thunderstorm and severe weather products as the same or better than counterpart SREF products, respectively.

CIWRO Themes: Forecast Application Improvements, Mesoscale and Stormscale Modeling
CIWRO Contributors: Kelsey Britt, Patrick Skinner
Project Title: System-relative probabilistic forecasts for quasi-linear convective system mesovortex tornado potential within WoFS
Relevance to NOAA: This project supports the NOAA mission by developing reliable probabilistic guidance products, improving weather and water predictions, and creating/improving a trusted analysis of record for model verification/nowcasting.

Quasi-linear convective systems (squall lines) account for 21% of U.S. tornado reports but have lower predictability and shorter lead times than supercell tornadoes. Forecasting squall line tornadoes is challenging due to their small, shallow, and transient nature. While the NWS uses the Significant Tornado Parameter to forecast supercell tornado potential, no equivalent parameter exists for squall line tornadoes. This study aims to develop a new composite forecast parameter for assessing squall line tornado potential within the WoFS that can provide useful probabilistic guidance before a tornado event. The parameter, QTor, combines near-storm environmental shear with information about local line geometry (orientation and curvature) to provide a system-relative forecast for squall line tornado potential. QTor's performance is evaluated using three tornadic squall line cases from 12 May 2022, 30 March 2022, and 15 December 2021. Results suggest the parameter is capable of effectively identifying portions of squall lines that are most favorable for tornado development, with lead times exceeding 2.5 hours. Tangible outcomes for this project include 1 conference presentation. One Ph.D. student was advised during this project.

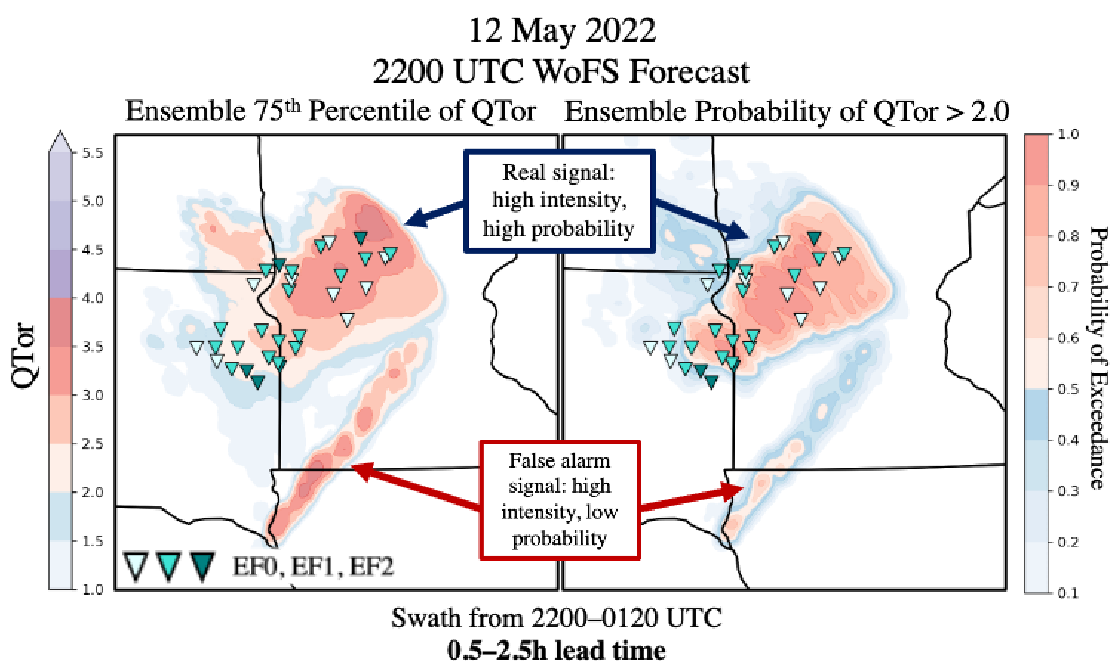


Figure 2-156: QTor (left) and the probability of QTor exceeding 2.0 (right) for the 2200 UTC WoFS forecast for the 12 May 2022 squall line case. QTor highlights the locations most favorable for tornado development that coincide with local tornado reports.

CIWRO Themes: Forecast Application Improvements, Mesoscale and Stormscale Modeling
CIWRO Contributors: Montgomery Flora, Joshua Martin, Brian Matilla, Kent Knopfmeier
Project Title: WoFSCast: A GraphCast emulator for thunderstorm scales
Relevance to NOAA: This project supports the NOAA mission by developing a next-generation weather modeling framework.

Developing AI models that match or exceed the forecast skill of numerical weather prediction (NWP) systems but run much more quickly is a burgeoning area of research. Most AI-NWP models, however, have been trained on global ERA5 data, which does not resolve storm-scale evolution. We have therefore adapted Google's GraphCast framework for limited-area, storm-scale domains, then trained on archived forecasts from WoFS, a convection-allowing ensemble with 5-min forecast output. We evaluate the WoFSCast predictions using object-based verification, grid-based verification, spatial storm structure assessments, and spectra analysis. The WoFSCast closely emulates the WoFS environment fields, matches 70-80% of WoFS storms out to 2-h forecast times, and suffers only modest blurring. Ongoing work explores the transition to an ensemble-based framework, incorporating higher resolution (1-km) into training and developing a complementary data assimilation scheme. Tangible outcomes include 2 publications, 2 conference talks, and a software release.

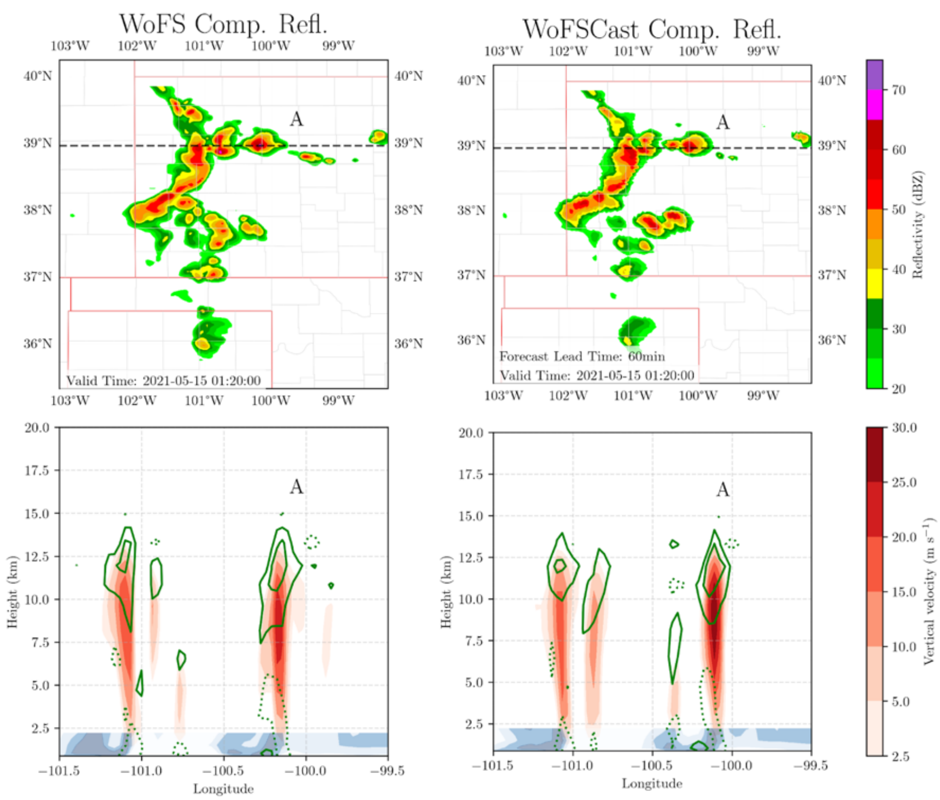


Figure 2-157: Comparison of a traditional NWP prediction (left column) against a fully AI prediction (right column) after 1 hour. Vertical cross-sections of updraft (red), divergence (green contours), and cold pool air (blue) are shown in the bottom panels.

CIWRO Themes: Forecast Application Improvements, Mesoscale and Stormscale Modeling
CIWRO Contributors: Patrick Skinner, Christopher Kerr, Derek Stratman, Monte Flora, Brian Matilla, Kent Knopfmeier, Joshua Martin, Thomas Jones, Nusrat Yussouf, Kelsey Britt
Project Title: Spatial verification of WoFS thunderstorm guidance
Relevance to NOAA: This project supports the NOAA mission by developing reliable probabilistic guidance products, improving weather and water predictions, creating/improving a trusted analysis of record for model verification/nowcasting.

Novel techniques developed for validating WoFS guidance are designed to provide useful information on forecast quality in WoFS predictions of convective storms and their associated hazards. Primarily, object- and grid-based spatial verification of WoFS guidance has been adapted to quantify forecast errors for specific problems associated with short-term prediction of thunderstorms. Studies have examined variation in WoFS skill between thunderstorm and mesocyclone predictions, between deterministic and probabilistic forecasts, between different storm modes, storm speeds, storm ages post convection initiation, across different locations within the WoFS domain, and in comparison, to other convection allowing forecast systems. Results from these studies serve two primary purposes: 1) Quantify system skill across a broad range of operational uses of WoFS guidance, establishing best practices for real-time use of the system, and 2) Identify primary sources of forecast error in WoFS, which guides future development. Tangible outcomes include contributions to 10 journal articles, 1 GRA advised, and over 20 conference presentations.

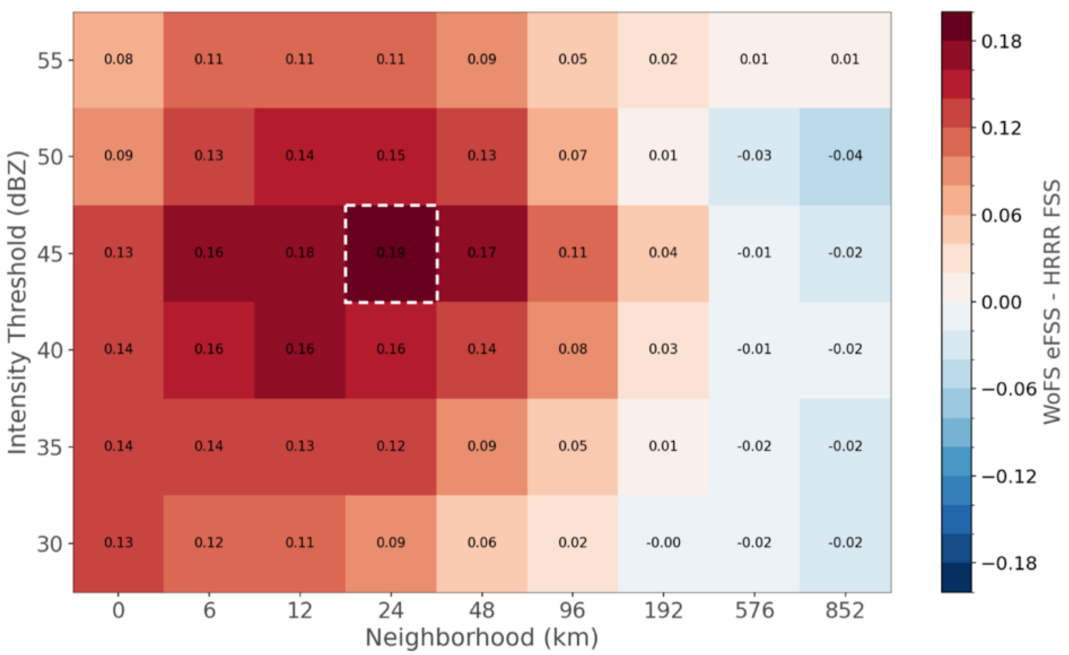


Figure 2-158: Extended Fractions Skill Score (eFSS) differences between WoFS simulated reflectivity and HRRR simulated reflectivity for 6-hour forecasts aggregated over 95 cases between 2020 and 2023. Individual bins are determined by reflectivity threshold (dBZ) and neighborhood width (km). Results indicate probabilistic thunderstorm guidance from WoFS improves over deterministic guidance for the majority of thresholds tested.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: David Harrison
Project Title: HREF calibrated thunder guidance
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and developing reliable probabilistic guidance products.

This project developed the High-Resolution Ensemble Forecast system (HREF) calibrated thunder guidance – a suite of probabilistic forecast products designed to predict the likelihood of at least one cloud-to-ground (CG) lightning flash within 20 km (12 miles) of a point during a given 1-, 4-, and 24-h time interval (Harrison et al. 2022). The guidance takes advantage of a combination of storm attribute and environmental fields produced by the convection-allowing HREF to improve upon lightning forecasts generated by the non-convection-allowing Short-Range Ensemble Forecast system (SREF). This study found the new guidance significantly outperformed existing lightning forecast products, and the HREF calibrated thunder guidance is now fully operational (readiness level 9) across the NWS. Tangible outcomes from this project include 1 technology transfer, 1 award-winning journal article (Harrison et al. 2022), and 2 conference presentations. This project was performed in collaboration with NCEP/SPC.

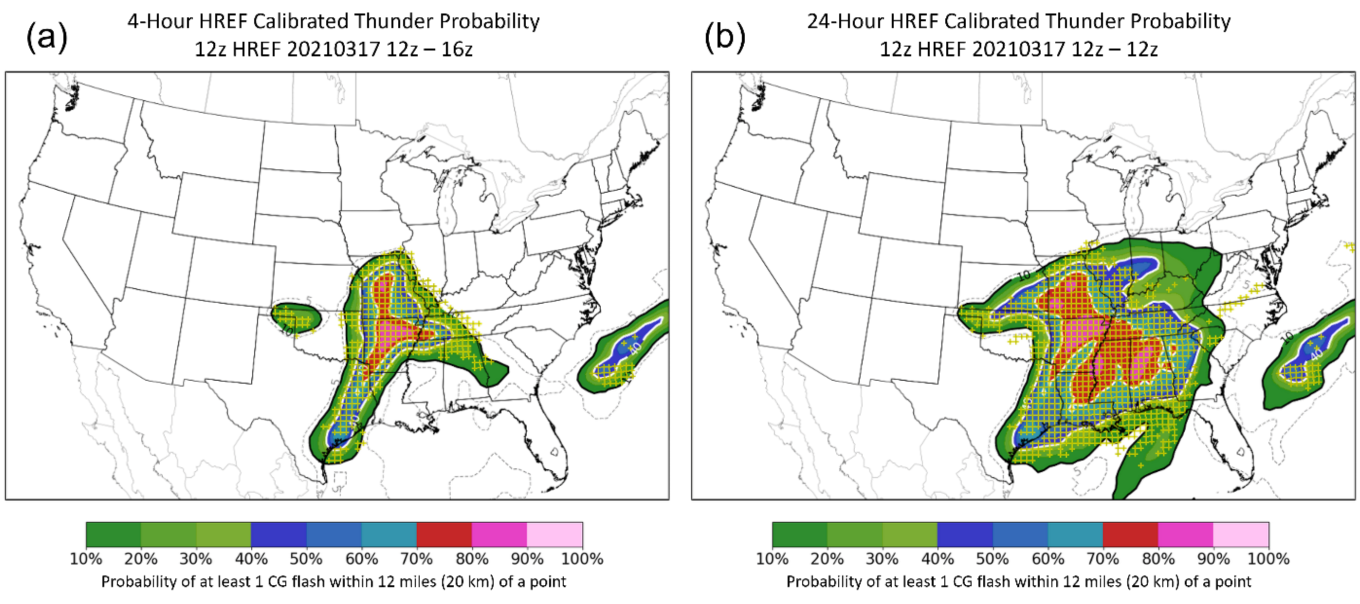


Figure 2-159: (a) 4- and (b) 24-h calibrated thunder forecasts from the 1200 UTC HREF cycle on 17 Mar 2021. Yellow "+" symbols indicate grid points where there was at least one CG lightning flash detected during the valid forecast period.

CIWRO Themes: Forecast Application Improvements
CIWRO Contributors: David Harrison
Project Title: HREF lightning density guidance
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and developing reliable probabilistic guidance products.

The HREF Calibrated Thunder guidance (HREFCT) is a suite of thunderstorm forecast products developed by CIWRO/SPC to predict the probability of at least one cloud-to-ground lightning flash within 12 miles (20 km) of a location during a given 1-, 4-, or 24-hour forecast period. This project further expands on the HREFCT to predict the probability of at least 25, 50, 100, or 200 CG flashes within 12 miles of a point during a 4-hour forecast period. This product, known as HREF lightning density guidance was directly requested by core NWS partners and has particular applications within the aviation, fire weather, and emergency management communities where frequent or spatially dense CG lightning may pose a greater risk to decision makers' constituents. This guidance is currently operational internally at SPC and is in the process of transitioning to full NWS operations (readiness level 9). Tangible outcomes from this project include 1 technology transfer and 2 conference presentations. This project was performed in collaboration with NCEP/SPC.

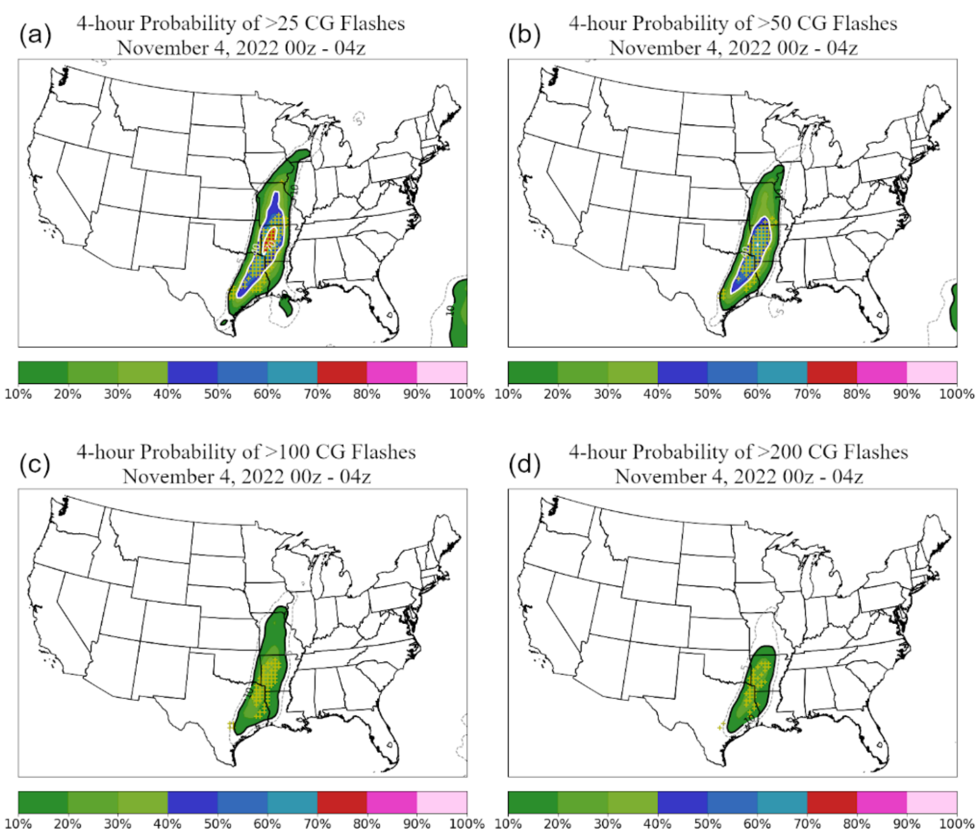


Figure 2-160: Probability of at least (a) 25, (b) 50, (c) 100, and (d) 200 CG flashes within 20 km of a point for 4 November 2022 0000z – 0400z. Yellow "+" markers indicate where the number of CG flashes exceeded the specified threshold.

CIWRO Themes: Forecast Application Improvements
CIWRO Contributors: Jake Vancil
Project Title: Deterministic and ensemble weather model verification
Relevance to NOAA: This project supports the NOAA mission by creating a trusted analysis of record for model verification; developing a next-generation water/weather modeling framework; and improving weather and water predictions.

This project provided important objective verification metrics for current and experimental deterministic and ensemble weather forecast systems. NOAA's USF goals aim to reshape the current operational weather model complex through the retirement of older and implementation of new weather models. It is important to fully understand the performance and biases of these new weather models prior to implementation to maintain the excellence of NWS/SPC's and others' operational weather forecasts. Major evaluations of this work include the assessment of the HRRRv4/RRFS, and HREF/REFS. Findings of this work directly influenced the future research, development, and implementation timelines of the RRFS and REFS forecast systems. Results have been extensively shared with interested stakeholders including SPC, NCEP/EMC, NSSL, and others. Verification metrics were calculated using the widely respected MET/METplus software package which is the standard for NOAA's UFS goals. Tangible outcomes from this project include 1 SPC/NSSL whitepaper, 2 Conference presentation, and 2 extended abstracts. External partners involved in this project include NCEP/SPC, NCEP/EMC, and OAR/NSSL.

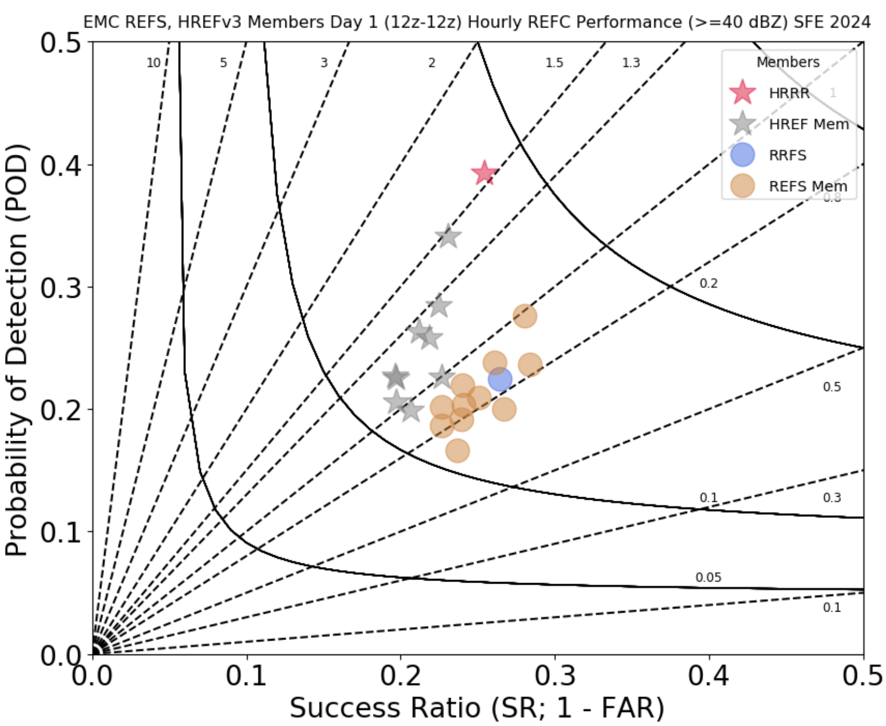


Figure 2-161: Performance diagram showing the performance of HREFv3 (stars) and REFS (circles) members in forecasting composite reflectivity of >=40 dBZ between 29 April 2024 – 31 May 2024. HRRRv4 (red star) and RRFS (blue circle) performance is also shown.

CIWRO Themes: Forecast Application Improvements
CIWRO Contributors: Jake Vancil, Andrew Wade
Project Title: Novel probabilistic hazard forecast verification improvements
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions, and creating/improving a trusted analysis of record for model verification.

This project applied innovative techniques to provide SPC forecasters with improved daily verification graphics of severe wind, hail, and tornado forecasts. Traditionally, SPC outlooks have been verified against local storm reports (LSRs) mapped to an 80-km grid. However, this method relies on the accuracy of LSRs and fails to account for known biases in LSR reporting across the country. This project aimed to improve upon the existing method by including storm warnings, public information statements, and radar derived intensity products (MRMS MESH, MRMS rotation tracks) in the verification calculations. Additionally, an analysis of prior SPC-issued probabilistic forecasts was used to further calibrate the truth probabilistic fields. These improvements were applied, and new verification graphics were provided to SPC forecasters through an internal. Tangible outcomes from this project include 1 internal SPC webpage, and 1 Conference presentation. External partners involved in this project include NCEP/SPC.

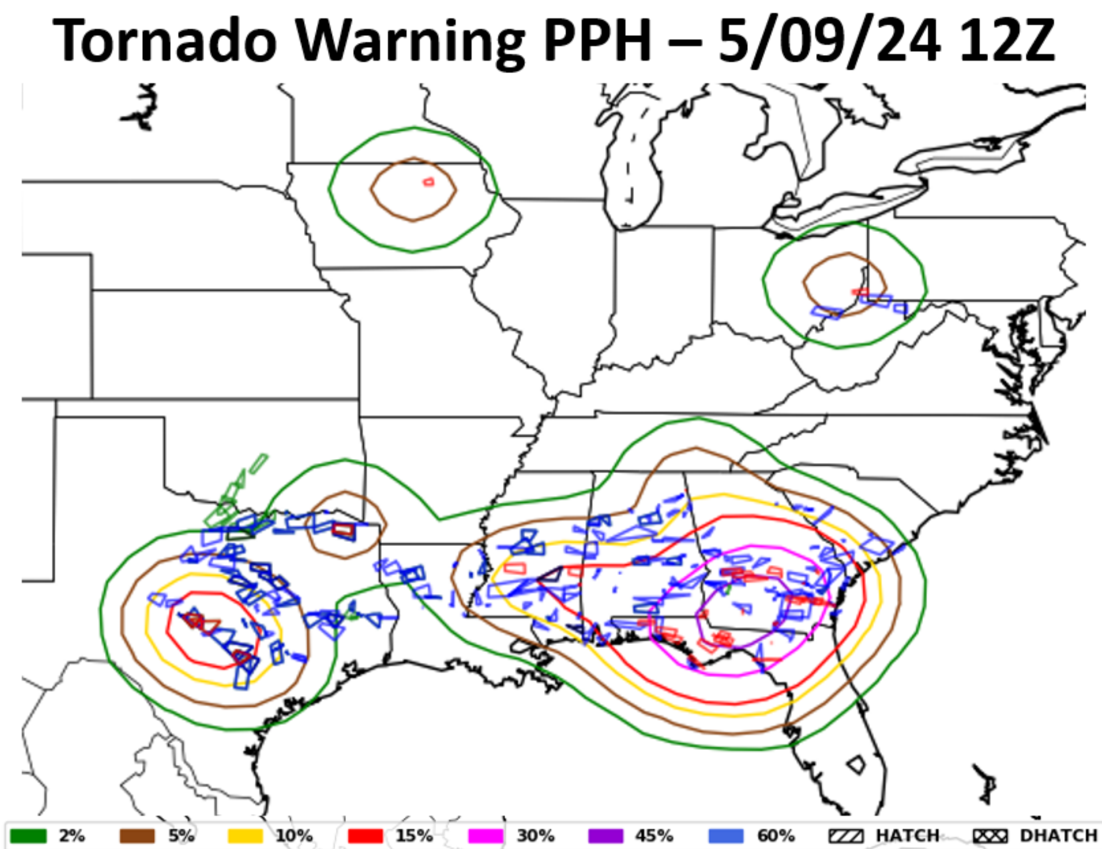


Figure 2-162: A tornado warning practically perfect hindcast for 9 May 2024 derived from tornado warnings. Tornado warnings are overlaid in the red polygons. Severe thunderstorm warnings are sorted by the NWS estimated magnitudes within the warning text to get wind (blue) and hail (green) warning polygons.

CIWRO Themes: Forecast Application Improvements, Mesoscale and Stormscale Modeling
CIWRO Contributors: Burkely Gallo, David Jahn
Project Title: Probabilistic calibrated tornado guidance
Relevance to NOAA: This project supports the NOAA mission by improving weather predictions, developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, developing reliable probabilistic guidance products.

In this project a probabilistic forecast guidance product was created that leverages a statistical relationship among tornado frequency and a storm index that incorporates environmental and storm-scale fields of the High Resolution Ensemble Forecast system (Jahn et al. 2022). A calibrated tornado guidance product is currently available daily to SPC forecasters, which highlights areas of various probability thresholds of predicted tornado occurrence within a 24-hour forecast period starting at 00z and 12z. Based on evaluations during multiple Spring Forecast Experiments, this product has provided useful information in the forecast of severity and areal coverage of tornado events (Jahn et al. 2022, 2023). This project produced 3 conference presentations, and project results were included in 3 BAMS articles. SPC was the primary external collaborator.

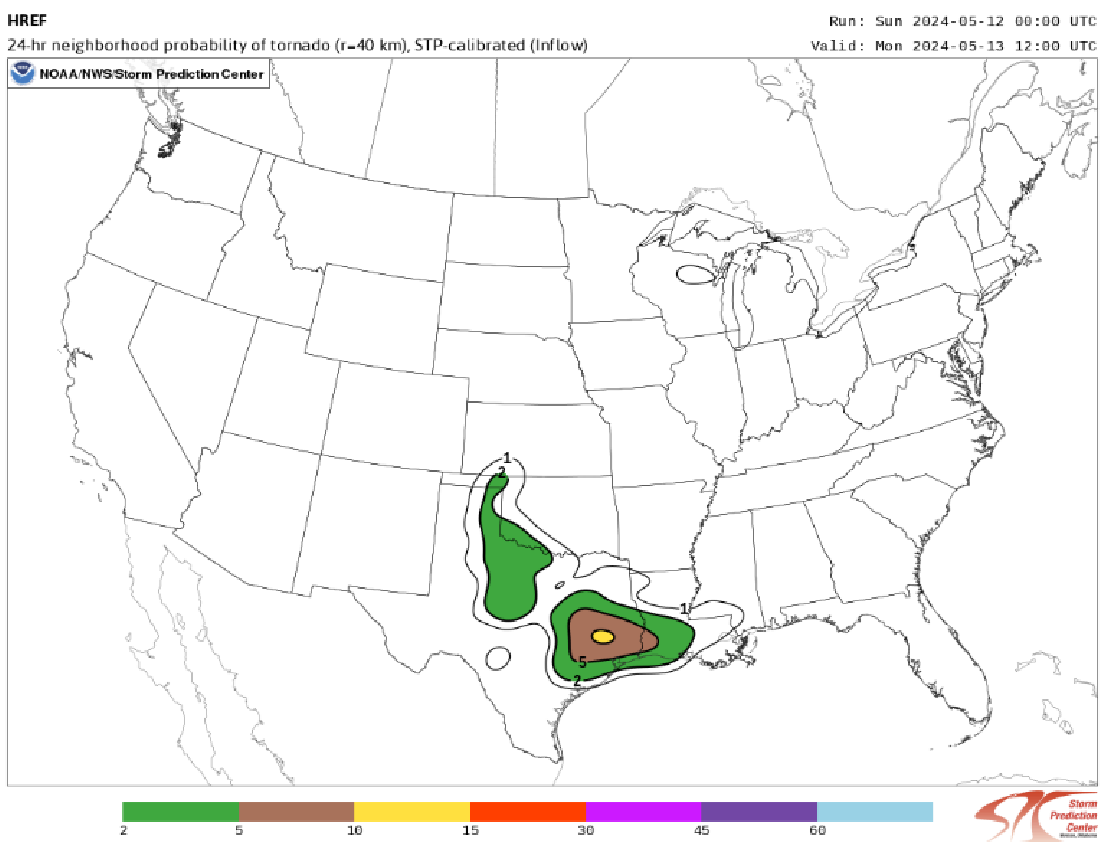


Figure 2-163: Forecast probability that a tornado will occur within 40-km of a point within a 24-hour forecast period beginning at 12 UTC for 05-13-2024.

CIWRO Themes: Forecast Application Improvements, Mesoscale and Stormscale Modeling
CIWRO Contributor: David Jahn
Project Title: Objective storm mode classification of a convection-allowing ensemble
Relevance to NOAA: This project supports the NOAA mission by improving weather predictions and developing reliable probabilistic guidance products.

In this project the probabilistic forecast of storm mode is determined by leveraging a noted differentiation among supercells and mesoscale convective systems (MCSs) based on the skewness value of the distribution of updraft helicity associated with a forecasted rotating storm of a convection-allowing ensemble, and specifically the High Resolution Ensemble Forecast (HREF). A dataset of subjectively characterized storm mode (700 cases) was used to train a linear regression model to forecast a probability of storm mode by range of updraft helicity skewness. Separate models were trained for each of the 5 HREF ensemble members. Using a test set of 120 cases, models for 3 of the 5 HREF ensemble members were able to differentiate MCSs from supercells (Jahn et al. 2024). The primary takeaway from this study is the potential importance of UH skewness as an additional parameter to use in storm mode classification. This study resulted in one conference presentation and involved collaboration with the SPC.

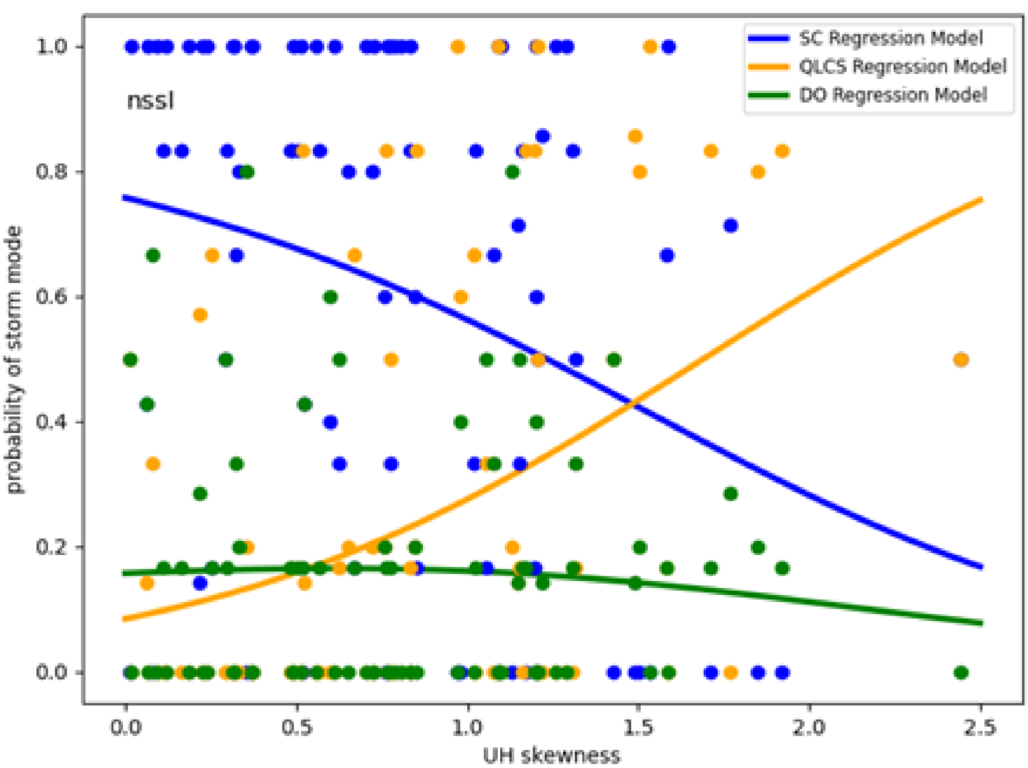


Figure 2-164: Scatter plot of storm mode probability (supercell, MCS, disorganized) as related to Updraft Helicity (UH) skewness for WRF NSSL (one of the 5 HREF ensemble members) survey cases. Lines represent linear regression models by storm mode showing a decrease (increase) in supercell (MCS) development with increase (decrease) in UH skewness.

CIWRO Themes: Forecast Application Improvements, Mesoscale and Stormscale Modeling
CIWRO Contributors: Andrew Wade, Anthony Lyza
Project Title: Regional and seasonal biases in convection-allowing model forecasts of near-surface temperature and moisture
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions; maturing the next-generation earth system models; and developing reliable probabilistic guidance products.

After months of maintaining a web page displaying real-time errors in operational convection-allowing model (CAM) forecasts of near-surface temperature and moisture, there appeared to be a cold bias in southeastern U.S. wintertime severe events. Two novel approaches were developed to target verification to observed and potential severe environments. The first centered model errors on filtered reports of tornadoes, using the Unrestricted Mesoscale Analysis as truth. The second identified Automated Surface Observing System (ASOS) observations meeting "warm sector" criteria of temperature, dewpoint, and wind, regardless of whether severe weather occurred nearby, and verified model forecasts against these observations. All five member models of the High-Resolution Ensemble Forecast (HREF; Roberts et al. 2019) system were evaluated, as well as a prototype of the experimental Rapid Refresh Forecast System (RRFS). The two largely independent verification techniques arrived at very similar results. In the Southeast cool season, both in storm inflow and in broader warm sectors, there was a robust cold bias of around 1 K across all models evaluated, with models using the Mellor-Yamada-. Janjíc MYJ Planetary Boundary Layer scheme averaging as low as -2 K. Results varied more among models and parameterizations for the Great Plains warm season. The Plains set was used primarily as a control to demonstrate the Southeast cool season bias, but useful tendencies of individual models, especially in moisture fields, were still shown. Tangible outcomes include 1 formal journal article and 1 conference presentation.

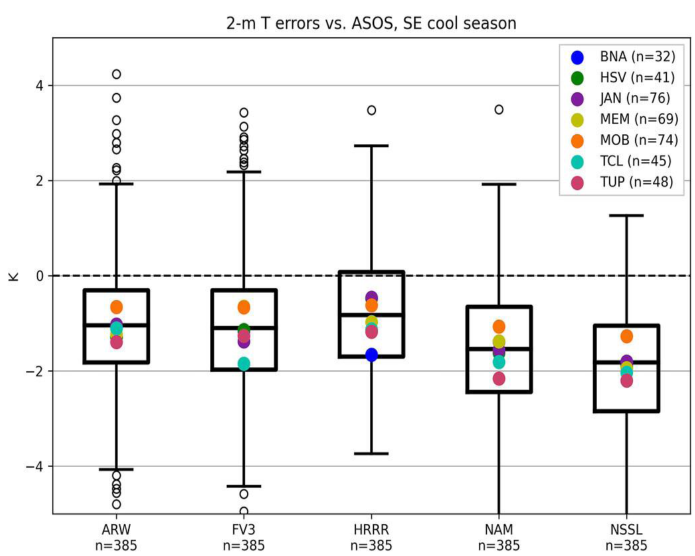


Figure 2-165: Boxplots of 2-meter temperature errors (K) in 6–12-h forecasts by each of HREF's five member models, for seven ASOS sites (colored dots marking site-specific medians) across the Southeast, in warm sector conditions, during the 2021–22 cool season.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributor: Bethany Earnest
Project Title: Machine-learning model for predicting wildfire occurrence
Relevance to NOAA: This project supports the NOAA mission by maturing the next-generation earth system models and developing reliable probabilistic guidance products

Wildfire represents a risk to life and property in many areas of the United States and is of growing concern to the public, legislative bodies, and insurance companies. A machine-learning model was developed to predict wildfire occurrence for the contiguous United States in the 0-to-10-day range using fuel, topography, and weather data, both observed and forecast. The model was trained using a fire occurrence database derived from the reports of federal, state, and local organizations. This model incorporates a deep learning approach, UNet3+, originally introduced for use in medical imaging, and is particularly skillful at image segmentation. Tangible outcomes from this project include 2 formal journal articles published, 2 formal journal articles to be submitted, and 4 conference presentations, one of which won the Outstanding Student Presentation Award, and another which won the Oral 2nd Place Award. External entities involved in this project include the NWS/SPC and the AI2ES. One GRA was supported.

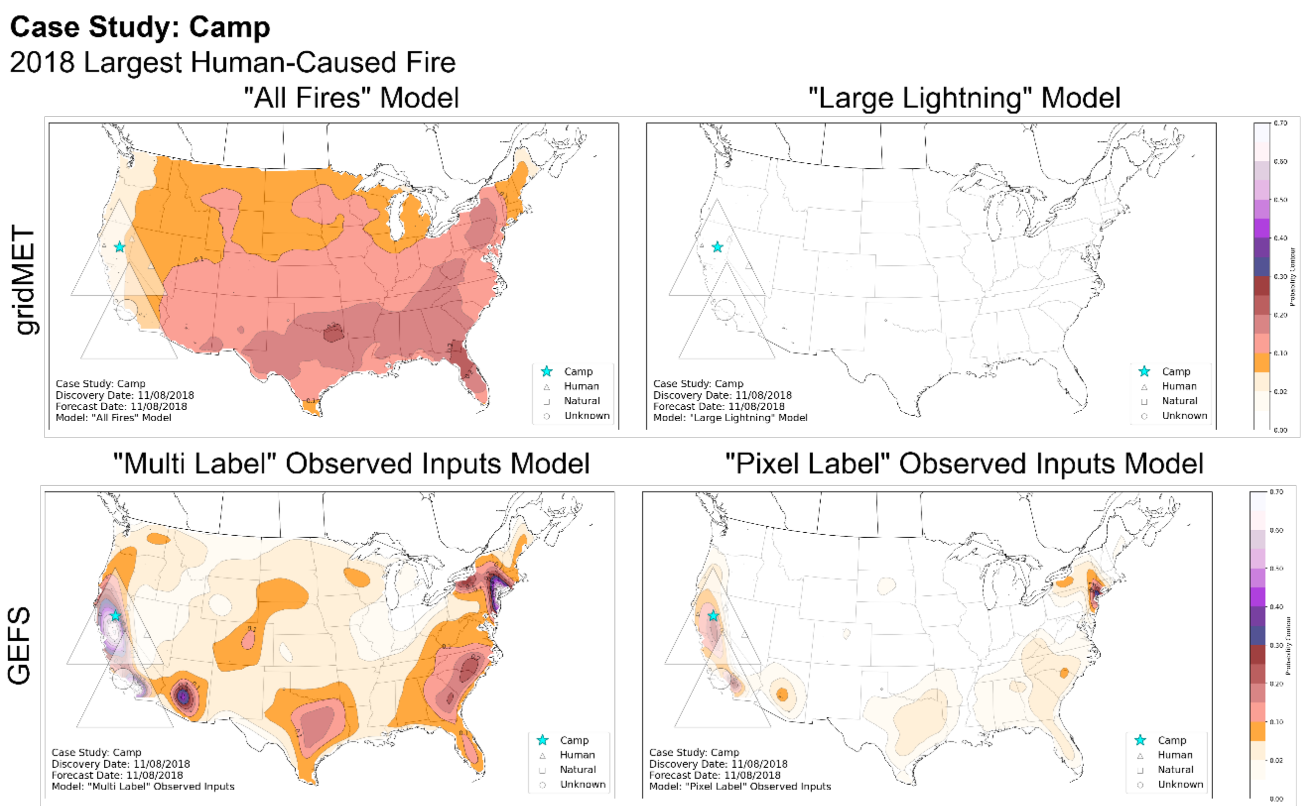


Figure 2-166: Examples of same day predictions for probability of fire occurrence for CONUS for the day of the Camp Fire (and the Woolsey Fire), 8 November 2018, predicted by four models using the UNet3+ model and model inputs from either gridMET or GEFS.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Heather Reeves, Michael Baldwin, Daniel Tripp, Andrew Rosenow
Project Title: Development of a probabilistic forecast of road temperatures
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and developing reliable probabilistic guidance products.

The primary factor that dictates whether snow or ice will accumulate on roads is the road temperature. Road temperatures may differ considerably from the surrounding landscape and, hence, are quite difficult to predict. The NWS currently has no decision support capabilities to anticipate whether roads are subfreezing. The aim of this research is to develop and advance an algorithm that provides a 0 to 100% probability that roads are subfreezing. The algorithm has been developed and tested within the MRMS framework and shows robust performance. Efforts since October 2021 include improving the algorithm's performance during heavy snow events (Baldwin et al. 2023) and incorporating algorithm output into an impacts-based decision support predictive system (Tobin et al. 2023a,b). The algorithm now runs in real time on the experimental MRMS system and is ready for transition into NWS operations. Tangible outcomes from this research include 3 journal articles, 4 conference presentations, and 1 algorithm ready for transition to NWS operations. External collaborators for this project include NCEP/WPC.

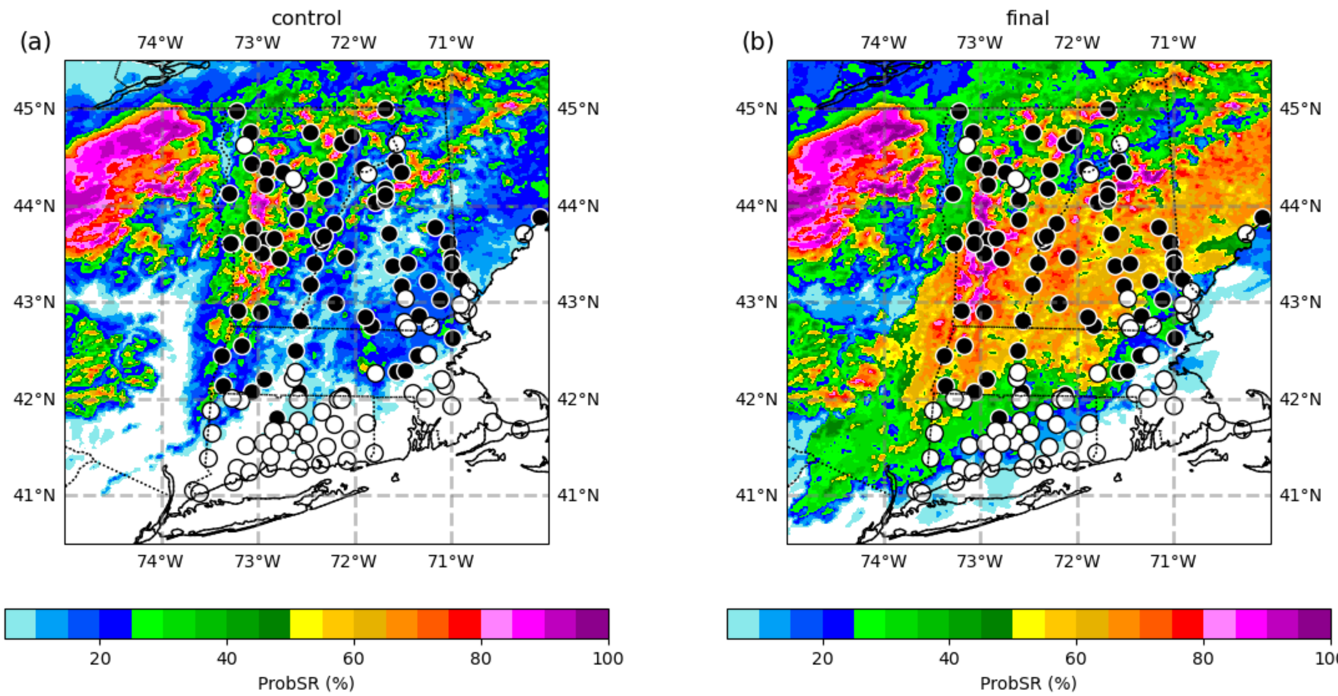


Figure 2-167: Probability of subfreezing road surface temperature (%; color shades) valid at 1800 UTC 23 Jan 2023 before and after algorithmic corrections. Black (white) dots indicate road temperatures that are below (above) 0°C.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributor: David Harrison
Project Title: First-guess watch guidance
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and developing reliable probabilistic guidance products.

This project developed a collection of machine-learning products that estimate where and when conditions will warrant the issuance of a severe thunderstorm or tornado watch. The guidance utilizes a gradient-boosted classifier trained on environmental fields and storm-derived parameters from the High-Resolution Ensemble Forecast System (HREF) and is designed to dynamically generate deterministic, county-based watches that provide up to three hours of lead time before severe weather occurs. These predictions are then input into a second gradient-boosted classifier that estimates whether a tornado or severe thunderstorm watch would be more appropriate in a given area based on the HREF's forecast environmental conditions. The first-guess watch guidance is intended to aid SPC forecasters in the planning of watches, mesoscale convective discussions, and other products up to 48 hours in advance of the severe weather threat. This guidance is currently running experimentally within SPC operations and has seen wide application by SPC forecasters over the past 2 years. Tangible outcomes from this project include 1 technology transfer, 1 web interface, and 5 conference presentations. This project was performed in collaboration with NCEP/SPC.

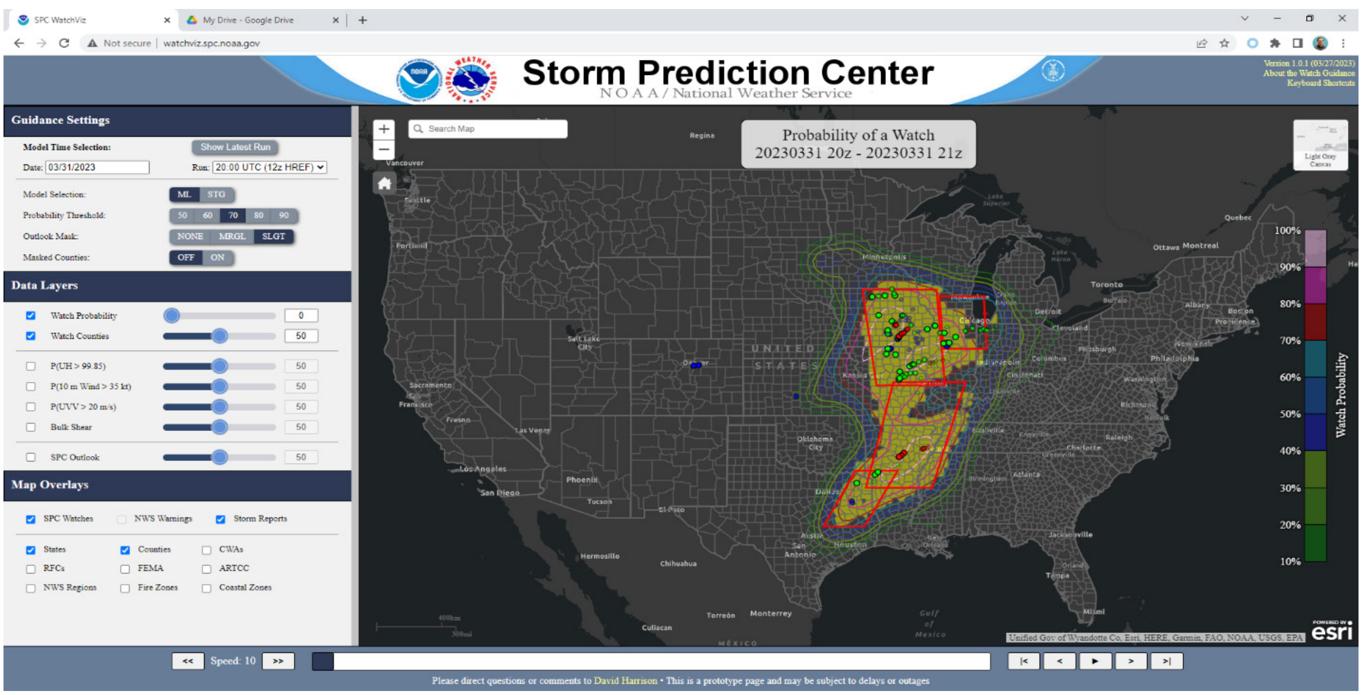
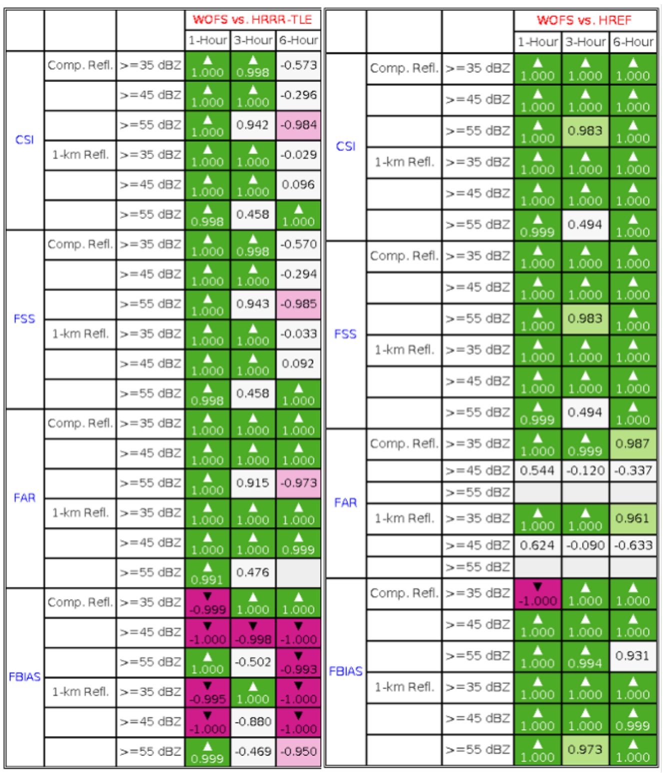


Figure 2-168: First-guess watch guidance and verification for 31 March 2023 21:00 UTC. Yellow counties represent where the guidance recommended a watch be issued at this forecast hour. The red polygons are Tornado Watches issued by the SPC for this valid time, and the red, blue, and green dots represent tornado, wind, and hail reports respectively.

CIWRO Themes: Forecast Application Improvements, Mesoscale and Stormscale Modeling
CIWRO Contributors: Brian Matilla, Nusrat Yussouf, Patrick Skinner, Kent Knopfmeier, Joshua Martin
Project Title: The WoFS scorecard using NOAA's Unified Forecast System Model Evaluation Tools (METplus) verification software
Relevance to NOAA: This project supports the NOAA mission by creating/improving a trusted analysis of record for model verification/nowcasting and developing reliable post-processing guidance products.

The WoFS is compared with a four-member, time-lagged High Resolution Rapid Refresh (HRRR-TLE) ensemble and the High Resolution Ensemble Forecast (HREF) using METplus software. The ensemble predicted composite reflectivity, low-level reflectivity, precipitation, and low and mid-level updraft helicity are against each other using MRMS and NCEP's stage IV data. Aggregated results from springtime (2018-2022) and summertime (2018-2020) WoFS cases show that WoFS generally provides significantly more accurate forecasts out to 3 hours of lead time when compared to HRRR-TLE and HREF, with mixed results at up to 6 hours of lead time. Tangible outcomes from this project include 2 conference presentations. External partners involved in this project include the Developmental Testbed Center.



			WOFS vs. HRRR-TLE		
			1-Hour	3-Hour	6-Hour
CSI	Comp. Refl.	>=35 dBZ	▲ 1.000	▲ 0.998	-0.573
		>=45 dBZ	▲ 1.000	▲ 1.000	-0.296
		>=55 dBZ	▲ 1.000	0.942	-0.984
	1-km Refl.	>=35 dBZ	▲ 1.000	▲ 1.000	-0.029
		>=45 dBZ	▲ 1.000	▲ 1.000	0.096
		>=55 dBZ	▲ 0.998	0.458	▲ 1.000
FSS	Comp. Refl.	>=35 dBZ	▲ 1.000	▲ 0.998	-0.570
		>=45 dBZ	▲ 1.000	▲ 1.000	-0.294
		>=55 dBZ	▲ 1.000	0.943	-0.985
	1-km Refl.	>=35 dBZ	▲ 1.000	▲ 1.000	-0.033
		>=45 dBZ	▲ 1.000	▲ 1.000	0.092
		>=55 dBZ	▲ 0.998	0.458	▲ 1.000
FAR	Comp. Refl.	>=35 dBZ	▲ 1.000	▲ 1.000	▲ 1.000
		>=45 dBZ	▲ 1.000	▲ 1.000	▲ 1.000
		>=55 dBZ	▲ 1.000	0.915	-0.973
	1-km Refl.	>=35 dBZ	▲ 1.000	▲ 1.000	▲ 1.000
		>=45 dBZ	▲ 1.000	▲ 1.000	▲ 0.999
		>=55 dBZ	▲ 0.991	0.476	
FBIAS	Comp. Refl.	>=35 dBZ	▼ -0.999	▲ 1.000	▲ 1.000
		>=45 dBZ	▼ -1.000	▼ -0.998	▼ -1.000
		>=55 dBZ	▲ 1.000	-0.502	▼ -0.993
	1-km Refl.	>=35 dBZ	▼ -0.995	▲ 1.000	▼ -1.000
		>=45 dBZ	▼ -1.000	-0.880	▼ -1.000
		>=55 dBZ	▲ 0.999	-0.469	-0.950

			WOFS vs. HREF		
			1-Hour	3-Hour	6-Hour
CSI	Comp. Refl.	>=35 dBZ	▲ 1.000	▲ 1.000	▲ 1.000
		>=45 dBZ	▲ 1.000	▲ 1.000	▲ 1.000
		>=55 dBZ	▲ 1.000	0.983	▲ 1.000
	1-km Refl.	>=35 dBZ	▲ 1.000	▲ 1.000	▲ 1.000
		>=45 dBZ	▲ 1.000	▲ 1.000	▲ 1.000
		>=55 dBZ	▲ 0.999	0.494	▲ 1.000
FSS	Comp. Refl.	>=35 dBZ	▲ 1.000	▲ 1.000	▲ 1.000
		>=45 dBZ	▲ 1.000	▲ 1.000	▲ 1.000
		>=55 dBZ	▲ 1.000	0.983	▲ 1.000
	1-km Refl.	>=35 dBZ	▲ 1.000	▲ 1.000	▲ 1.000
		>=45 dBZ	▲ 1.000	▲ 1.000	▲ 1.000
		>=55 dBZ	▲ 0.999	0.494	▲ 1.000
FAR	Comp. Refl.	>=35 dBZ	▲ 1.000	▲ 0.999	0.987
		>=45 dBZ	0.544	-0.120	-0.337
		>=55 dBZ			
	1-km Refl.	>=35 dBZ	▲ 1.000	▲ 1.000	0.961
		>=45 dBZ	0.624	-0.090	-0.633
		>=55 dBZ			
FBIAS	Comp. Refl.	>=35 dBZ	▼ -1.000	▲ 1.000	▲ 1.000
		>=45 dBZ	▲ 1.000	▲ 1.000	▲ 1.000
		>=55 dBZ	▲ 1.000	▲ 0.994	0.931
	1-km Refl.	>=35 dBZ	▲ 1.000	▲ 1.000	▲ 1.000
		>=45 dBZ	▲ 1.000	▲ 1.000	▲ 0.999
		>=55 dBZ	▲ 1.000	0.973	▲ 1.000

Figure 2-169: Example of a scorecard comparing the Critical Success Index (CSI), Fractions Skill Score (FSS), False Alarm Ratio (FAR), and Frequency Bias (FBIAS) of composite reflectivity and 1-km reflectivity for WoFS versus HRRR-TLE and WoFS versus HREF from 2018-2022 springtime cases. Green colors indicate that WoFS performed better, while pink colors indicate that WoFS performed worse. Statistical significance values are printed inside of each hourly column.

CIWRO Themes: Forecast Application Improvements, Social and Socioeconomic Impacts of High-Impact Weather Systems, Subseasonal-to-Seasonal Prediction for Extreme Weather
CIWRO Contributors: Joseph Picca, Jacob Vancil
Project Title: The development of a quantitative tornado counts prediction system
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions.

In this project a new forecaster-support tool is developed for internal use at the SPC. This product culminates with data output during the quality-control process of a convective outlook and includes predictions of tornado counts and unconditional probabilities of various tornado intensities, implied by the forecaster's severe weather outlook. It is intended to provide more context for and understanding of the new conditional-intensity forecast paradigm, currently in the experimental phase at the SPC. Objective verification of these data indicates that they provide reliable estimates of tornado counts and have helped forecasters better embrace the idea of conditional intensity forecasting. Tangible outcomes from this project include 1 conference presentation and an experimental workflow currently in use at the SPC. External partners involved in this project include the NCEP/SPC and NWS/OSTI.

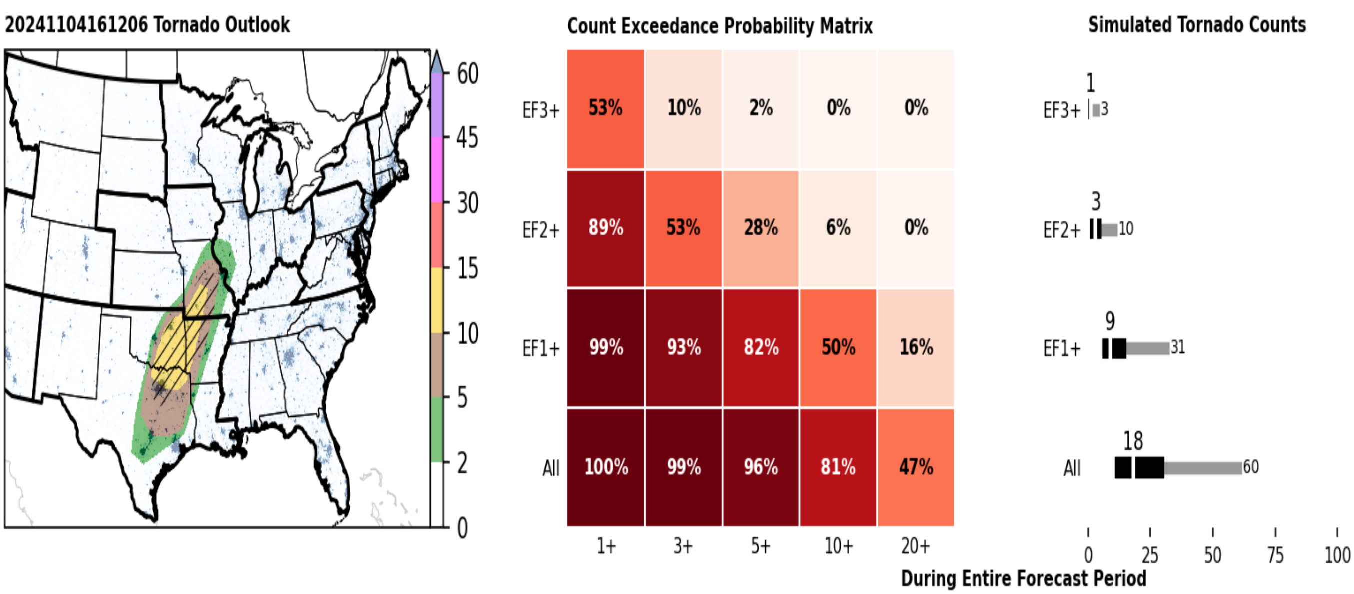


Figure 2-170: Simulated tornado counts for the SPC's 20241104 12z convective outlook.

CIWRO Themes: Forecast Application Improvements, Mesoscale and Stormscale Modeling
CIWRO Contributors: Michael Baldwin, Monte Flora, David Harrison, Kimberly Hoogewind, Chris Kerr, Pat Skinner, Derek Stratman, Nusrat Yussouf, Andrew Wade
Project Title: Improved understanding of forecast evaluation techniques
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions, incorporating social-science principles in new technology/training, and developing reliable probabilistic guidance products.

Prediction systems are typically developed and improved by optimizing evaluation measures, such as critical success index, or squared error. The ramifications of the selection of verification approaches in the forecast system development cycle are not fully understood. There may be unintended consequences resulting from these choices, such as system updates producing more useful forecasts for a subset of decision-makers, while making them less useful for others. In this project, advanced techniques of forecast evaluation have been developed that allow for improved understanding of multiple aspects of forecast performance. This includes evaluating forecasts in terms of the types of decision-makers that can benefit from using forecast information. Research into the history of widely used verification measures has also led to improved understanding of the behavior and sensitivity of these approaches (Brooks et al. 2024), especially for rare events. These techniques have been applied to a variety of products, such as heavy rainfall forecasts, operational severe weather outlooks, medium-range guidance products generated by machine learning algorithms, and experimental high-resolution ensemble numerical modeling systems (WoFS). Tangible outcomes from this project include 1 formal journal article and 3 conference presentations. External partners involved in this project include NCEP/SPC, OU, and NCEP/WPC.

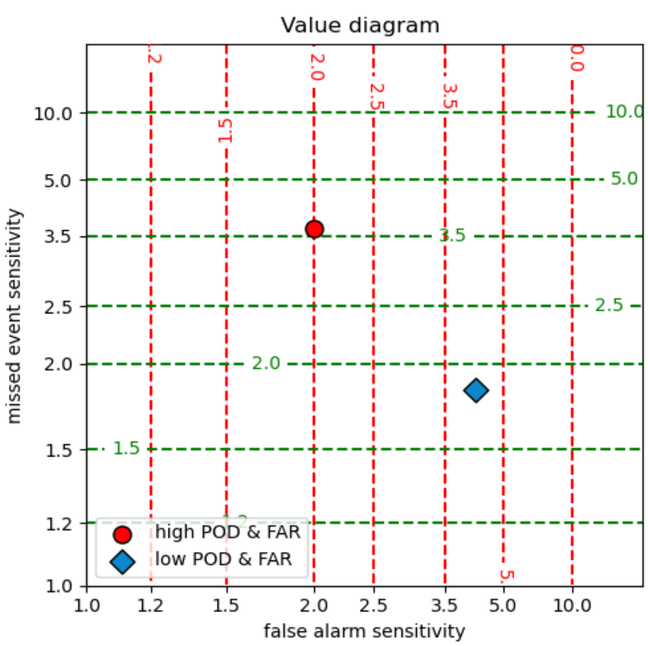


Figure 2-171: Example of a "Value diagram". Two generic forecast systems are displayed in terms of the range of users with sensitivities to missed events (y-axis, green dashed) and false alarms (x-axis, red dashed) that can benefit from the forecast information.

CIWRO Themes: Forecast Application Improvements, Weather Radar and Observations
CIWRO Contributors: Thea Sandmæl, Rebecca Steeves, Jonny Madden, Brandon Smith, Patrick Campbell, Justin Monroe, Claire Satrio, Jacob Segall, Ryan Martz, Eric Loken, Zachary Fruits, Isaiah Schick, Marcus Ake, Zachary Cooper, Jacob Widanski, Quinton Thomas, Roy Galang, Rosa Mwakyoma, Benjamin Kassel, Alexa Dringus, Danielle Crutchfield, Ben Schenkel, Pat Hyland
Project Title: The tornado probability algorithm (TORP)
Relevance to NOAA: This project supports the NOAA mission by developing reliable probabilistic guidance products.

The Tornado Probability Algorithm (TORP) is a machine learning-based single-radar algorithm that provides probabilities that a tornado is occurring or developing in the next 30 minutes. It uses radar data from a single low-level tilt as input into a random forest model to calculate tornado probabilities. TORP uses azimuthal shear to identify areas of high rotation to create automated tornado detection objects. TORP then tracks these objects in time to show how radar characteristics of a storm circulation have evolved as shown in the attached figure. TORP can be used in AWIPS-II or in the prototype Probabilistic Hazards Information (PHI) prototype tool, and includes functionalities for filtering by a number of fields associated with the detection (e.g., tornado probability, trends). TORP has been tested by NWS, SPC, and Air Force forecasters in multiple HWT experiments in 2021–2024. TORP is currently running in real time, and is provided in a simplified form to multiple NWS test offices in the NWS Southern and Eastern regions. These offices provide real-time feedback on TORP. TORP has been used to help issue tornado warnings and, more broadly, has been found to be a useful tool in simulated severe weather warning operations. Tangible outcomes from this project include two formal journal articles, six conference presentations, eleven undergraduates supervised, one funded proposal, and one algorithm ready for transition to NWS operations. External partners involved in this project include NWS, NWS/SPC, and NWS/ROC.

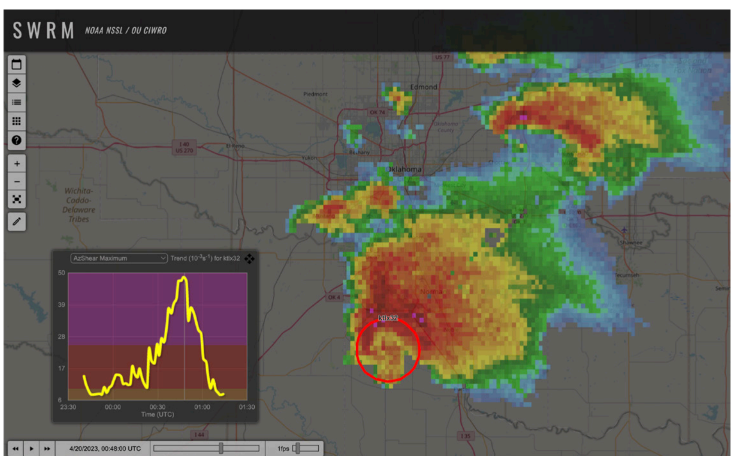


Figure 2-172: Example of a TORP detection associated with a supercell from 20 April 2023 in Severe Weather Research Map. TORP is represented by a red circle, and the maximum azimuthal shear evolution over the storm's lifecycle can be seen on the lefthand side of the figure.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Patrick Campbell, Claire Satrio, Rebecca Steeves
Project Title: Advances in Probabilistic Hazard Information (PHI)
Relevance to NOAA: This project supports the NOAA mission by developing reliable probabilistic guidance products and developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

Probabilistic Hazard Information (PHI) for severe weather hazards provides rapidly updating threat levels and spatial and temporal distributions for tornadoes, wind, hail, and lightning within the next 1-2 hours. PHI incorporates automated probabilistic threat guidance that is derived from machine learning algorithms such as the Tornado Probability Algorithm (TORP), ProbSevere, and ProbLightning and is created every two minutes. Since Oct. 2021, advances have been made in the generation, accuracy, application, and distribution of PHI. Two HWT evaluations over six weeks in 2022 and 2023 led to advances in PHI research related to the interaction between PHI and warnings, mitigation of forecaster workload, projected storm motion, and communication of threat information to decision makers. Since 2023, collaboration with the NWS has allowed operational WFO forecasters access to and the ability to provide critical insight into the latest PHI research, leading to important feedback for iterative development. Significant advances in the stability of automated guidance (Satrio et al. 2023) have proven extremely valuable to PHI research and collaboration efforts. The application of PHI to community risk guidance has also been investigated (Kim et al. 2022, Kim et al. 2023), and the usage of PHI by end users such as broadcast meteorologists has been studied (Obermeier et al. 2023). Tangible outcomes from this project include 12 conference presentations, 4 journal articles, 2 testbed evaluations, and 1 transition to a live system. External partners involved in this project include the NSSL, Global Systems Laboratory, NWS Southern Region, and NWS Eastern Region.

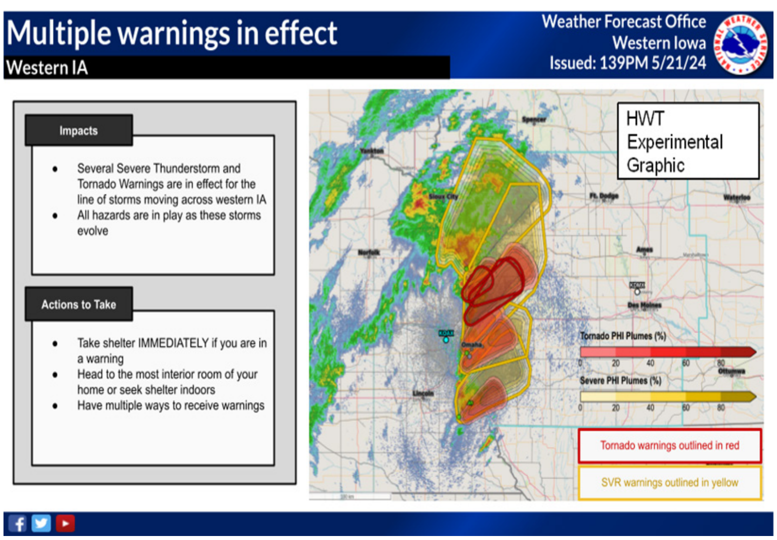


Figure 2-173: Experimental communication graphic created during an HWT evaluation showing Probabilistic Hazard Information (PHI). Shown are tornado threats (red) and severe wind/hail threats (yellow), where darker shading indicates higher probability of strike and solid outlines indicate threat warning.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Eric Loken, Thea Sandmael, Ryan Martz, Patrick Skinner
Project Title: Warn-on-Forecast System - Probabilistic Hazard Information (WoFS-PHI)
Relevance to NOAA: This project supports the NOAA mission by developing reliable probabilistic guidance products.

WoFS-PHI uses random forests to obtain probabilistic spatial forecasts of severe weather hazards based on predictors from the WoFS (Heinselman et al. 2024), ProbSevere (Cintineo et al. 2020, 2024), and the Tornado Probability Algorithm (TORP; Sandmael et al. 2023). Objective verification shows that random forests using both WoFS and ProbSevere predictors make better forecasts than those using either WoFS or ProbSevere predictors alone. Analysis with Tree Interpreter (Saabas 2016; Loken et al. 2022) shows that WoFS-PHI generally places more importance on ProbSevere predictors in the first 30-60 minutes of lead time and more importance on WoFS predictors thereafter. The greatest benefit to using WoFS-PHI comes at lead times of 30-90 minutes, when WoFS and ProbSevere are about equally important. WoFS-PHI was implemented in real-time on the WoFS Viewer in the spring of 2024. In the 2024 HWT-Spring Forecasting Experiment (HWT-SFE), participants who had access to WoFS-PHI made higher-rated forecasts than those without (Clark et al. 2024). WoFS-PHI was also evaluated in the 2023 SFE and the 2023 and 2024 HWT Watch-to-Warning experiments. Tangible outcomes include 8 conference presentations, 1 software release, and 4 HWT experiments. The project supported 1 GRA (OU master's student).

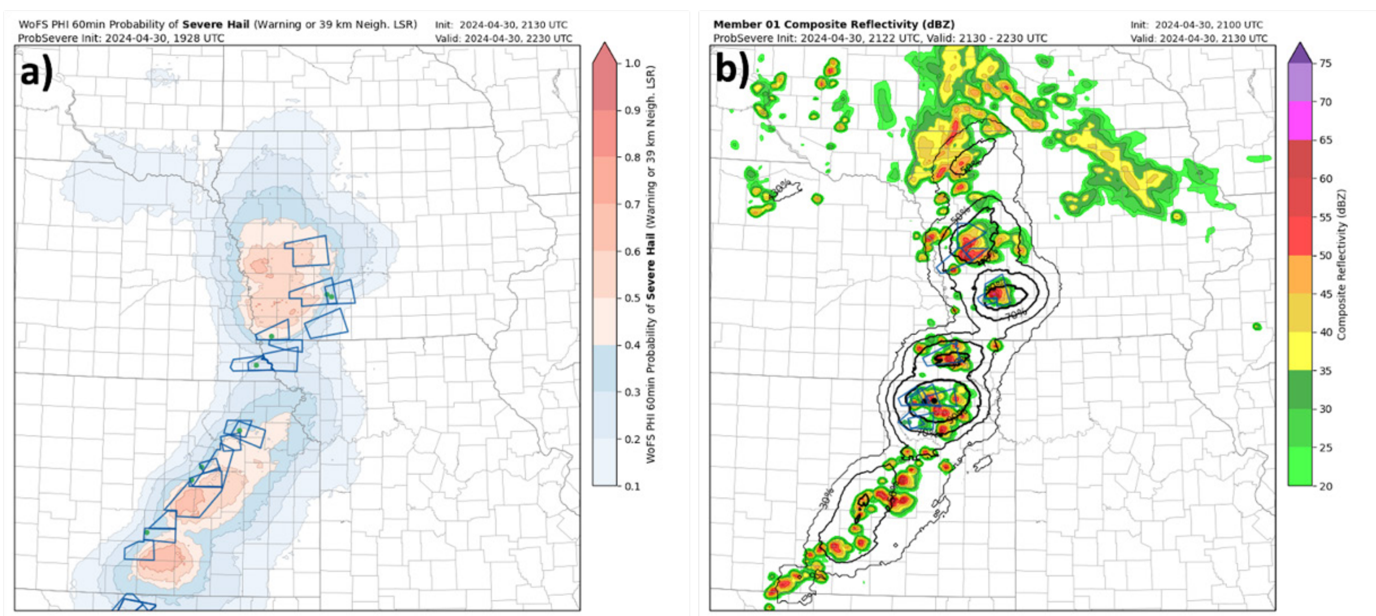


Figure 2-174: Example WoFS-PHI hail forecast products from 30 April 2024, both valid from 2130-2230 UTC on 30 April 2024. (a) "Forecast mode" WoFS-PHI (shaded), created at 1928 UTC (representing a ~2-3 h forecast). (b) "Warning mode" WoFS-PHI forecast (black contours), created at 2122 UTC (representing a ~5-65-minute forecast), overlaid on simulated reflectivity from member 1. In both panels, 30-minute observed hail reports (green dots) and severe thunderstorm warnings (blue contours) are overlaid; note that these do not cover the full valid period.

CIWRO Themes: Forecast Application Improvements, Weather Radar and Observations
CIWRO Contributors: Edwin Lee Dunnavan, Jacob Carlin, John Krause
Project Title: Predicting fallout of heavy snow at the surface using polarimetric signatures aloft
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions, enhancing capabilities for RadarNext program and/or WSR-88Ds, and creating/improving a trusted analysis of record for model verification/nowcasting.

This project develops a NEXRAD algorithm for nowcasting of heavy snow using WSR-88D radar volumes. The algorithm utilizes K_{DP} enhancements in the dendritic growth layer to initialize Lagrangian trajectories. These trajectories are computed using assumed snow fall speeds and RAP model winds. Heavy snow nowcast probabilities are computed using Practically Perfect Forecasts (Hitchens et al. 2013) that are constructed using the endpoint locations of the Lagrangian trajectories. The algorithm was tested on 30 WSR-88D cases involving a diverse set of snow systems including snow squalls, lake effect snowstorms, and synoptic snowstorms. The median Brier skill scores, threat scores, and point biserial coefficients for all volumes from all 30 cases were 0.23, 0.47, and 0.63, respectively. This project has resulted in 3 Technical Interchange Meeting presentations.

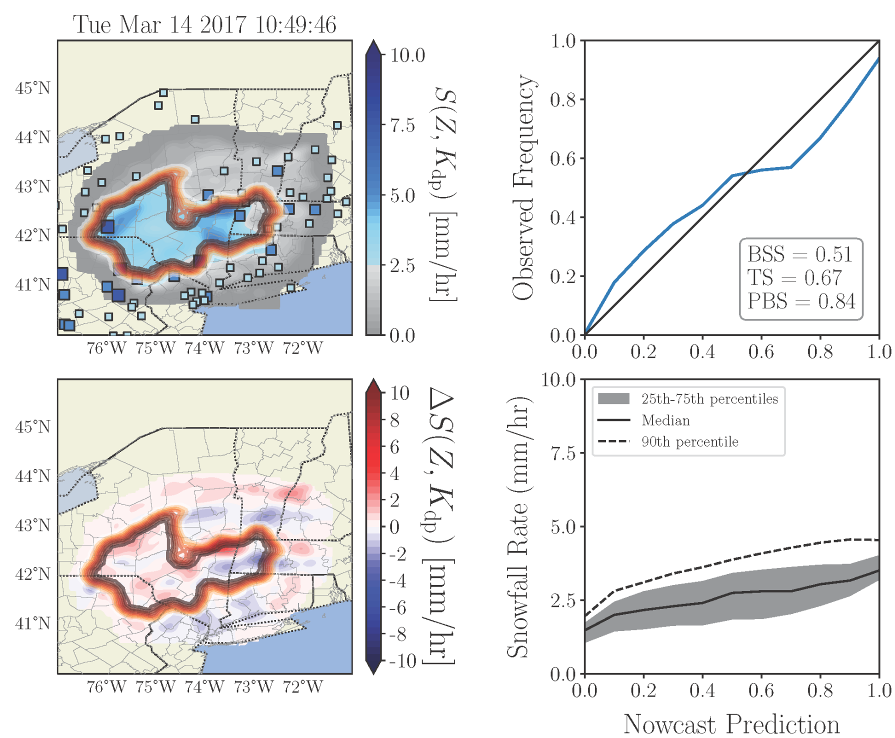


Figure 2-175: Example output of the heavy snow nowcasting NEXRAD algorithm. (Top left) Lowest level (500-m) CAPPIs of equivalent snow rate (filled) with practically perfect forecast contours (orange/black lines) at the evaluation time. (Top right) Reliability diagram of forecast compared to 500-m CAPPI snow rates at evaluation time. (Bottom left) As in top left but with the difference in snow rate from the evaluation time to the trajectory initialization time. (Bottom right) Percentiles of snow nowcast forecast probabilities and observed snow rates at evaluation time.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Steven Martinaitis, Dean Meyer, Jackson Anthony
Project Title: Evaluation of ensemble nowcasting settings for MRMS
Relevance to NOAA: This project supports the NOAA mission by Improving weather and water predictions and developing reliable probabilistic guidance products.

This project evaluated the use of the high resolution MRMS QPE data within the Short-Term Ensemble Prediction System (STEPS) nowcasting system. The testing conducted with STEPS was based on the various tunable parameters. A series of flash flood cases that were a result of heavy rainfall were evaluated within the STEPS program based on the different combination of parameter settings (advection tracking threshold, number of ensemble members, and use of perturbating the advection field) as well as different MRMS resolutions (1-km, 500-m). The results of the study found that changing some of the parameters had some influence on the nowcasting performance and associated probabilistic guidance but were generally not statistically significant; moreover, the lack of difference with fewer ensemble members means that the model can be ran more quickly and still retain the same level of accuracy. Findings from the project can inform how to move forward with nowcasting within the MRMS system either through the use of STEPS or to set a benchmark to compare with other nowcasting of short-term forecasting systems (e.g., Warn-on-Forecast System). Ultimately, the work here can help lead to improved forcing for FLASH with flash flood warning operations and forcing for the NWM for hydrologic flood prediction. Tangible outcomes from this project are 3 conference presentations, 1 journal article (in review), and 1 summer REU student mentorship.

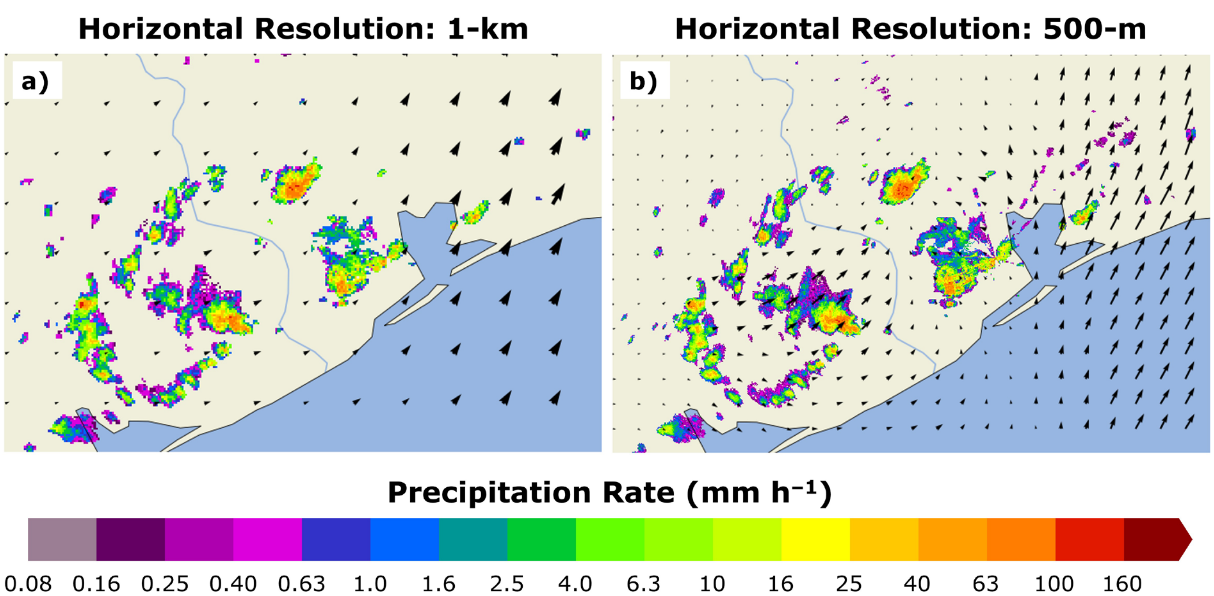


Figure 2-176: Comparison of the nowcast advection motion vectors using 1-km resolution (left) versus 500-m resolution (right) MRMS instantaneous rain rates for an event over Houston, TX at 1930 UTC 21 July 2021. A rate tracking threshold setting of 0.5 mm h-1 was used to create the advection motion vectors.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributor: Heather Reeves
Project Title: The development of recommender for convective avoidance in aviation
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events

A marquee product of the NCEP/AWC's product suite is the Convective SIGMETs (C-SIGs). C-SIGs are considered critical for national security, but the methods used to produce these have changed very little since they were first introduced in the early 1980s. Humans still manually update and characterize up to 30 polygons an hour. This project focuses on simulating the human process of drawing polygons that meet the various requirements/limitations on the dissemination of C-SIGs. Automated C-SIGs have been evaluated in a testbed setting and are now running live on the experimental MRMS system for continued evaluation. Tangible outcomes from this project include 5 conference presentations and 1 WMO recommendation. External partners involved in this project include NCEP/AWC and the FAA.

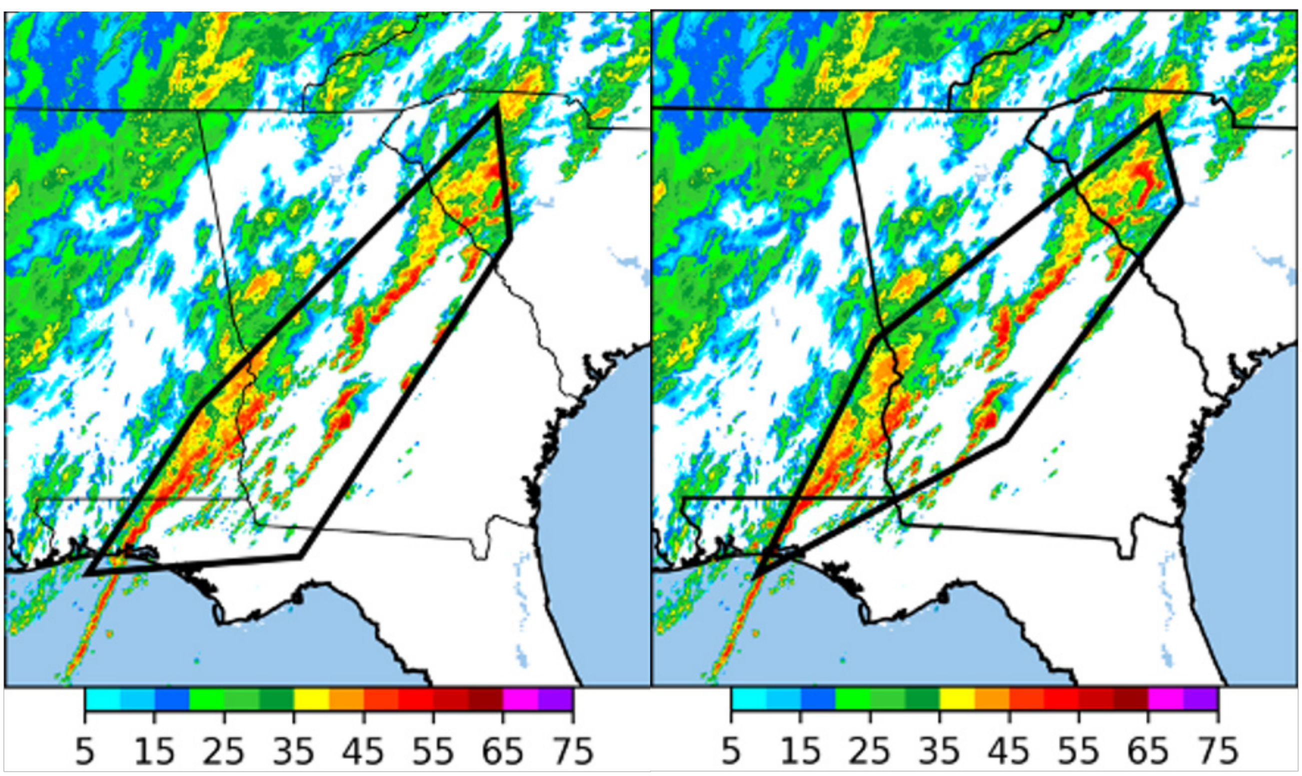


Figure 2-177: An example of a (a) manually generated C-SIG issued by the AWC and (b) an automated one generated by our software. Both images are valid at 2100 UTC 17 January 2020.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: David Harrison, David Jahn, Jake Vancil, Joey Picca, Kevin Thiel, Cameron Nixon, Andrew Wade, Mike Baldwin, Nathan Dahl, Kelton Halbert, Jeff Milne
Project Title: HWT spring forecasting experiment
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions; developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events; and developing reliable probabilistic guidance products.

The CIWRO/SPC team is instrumental in the coordination, facilitation, execution, and post-assessment of the HWT Spring Forecasting Experiment (HWT SFE). This testbed evaluates and showcases experimental severe weather forecast products from multiple NOAA agencies, academia, and private institutions to provide formal, quantifiable feedback to developers. This work requires annual development and maintenance of custom software to manage the generation of day-to-day operational products, coordinating dataflows and survey design with external partners, and applying both novel and standardize verification and analysis techniques to derive objective and subjective conclusions about the experimental products. These efforts serve as a critical link between researchers, developers, and forecasters in the R2O process and enable improved communication and co-production between all invested parties. Tangible outcomes from this project thus far include at least 4 journal articles (Clark et al. 2022, 2023a, 2023b, 2024), 3 summary reports, and an unknown number of conference presentations. External partners involved in this project include NCEP/SPC, OAR/NSSL, NCEP/GFDL, UKMET office, NCEP/EMC, NWS, Iowa State University, OU, Texas Tech University, and others.

Photo 2-7: Participants and facilitators review experimental forecast products during the 2024 HWT Spring Forecasting Experiment.

CIWRO Themes: Forecast Application Improvements, Weather Radar and Observations
CIWRO Contributors: Kevin Thiel, Justin Monroe, Jonathan Madden
Project Title: Satellite convective applications experiment in NOAA’s HWT
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions; improving observation quality and/or stewardship; and developing next-generation observational capabilities.

The Satellite Convective Applications Experiment, funded by the GOES-R/JPSS Proving Ground, is an annual testbed that demonstrates experimental satellite products and their ability to support the short-term forecasting and communication of severe and hazardous weather. Product developers from federal and university institutions demonstrate their products in live, real-time severe weather scenarios with NWS forecasters from across the agency. Participant feedback drives improvements to product quality, visualization techniques, training materials, and operational implementation strategies. Results from the experiment have contributed to now-operational products such as probabilistic lightning guidance from a satellite-based machine learning model (ProbSevere LightningCast). Tangible outcomes from the project include 3 published reports (Thiel 2022, Thiel 2023, Thiel 2024) and 9 conference presentations. External partners have included three NOAA cooperative institutes, three universities, and two NASA centers.

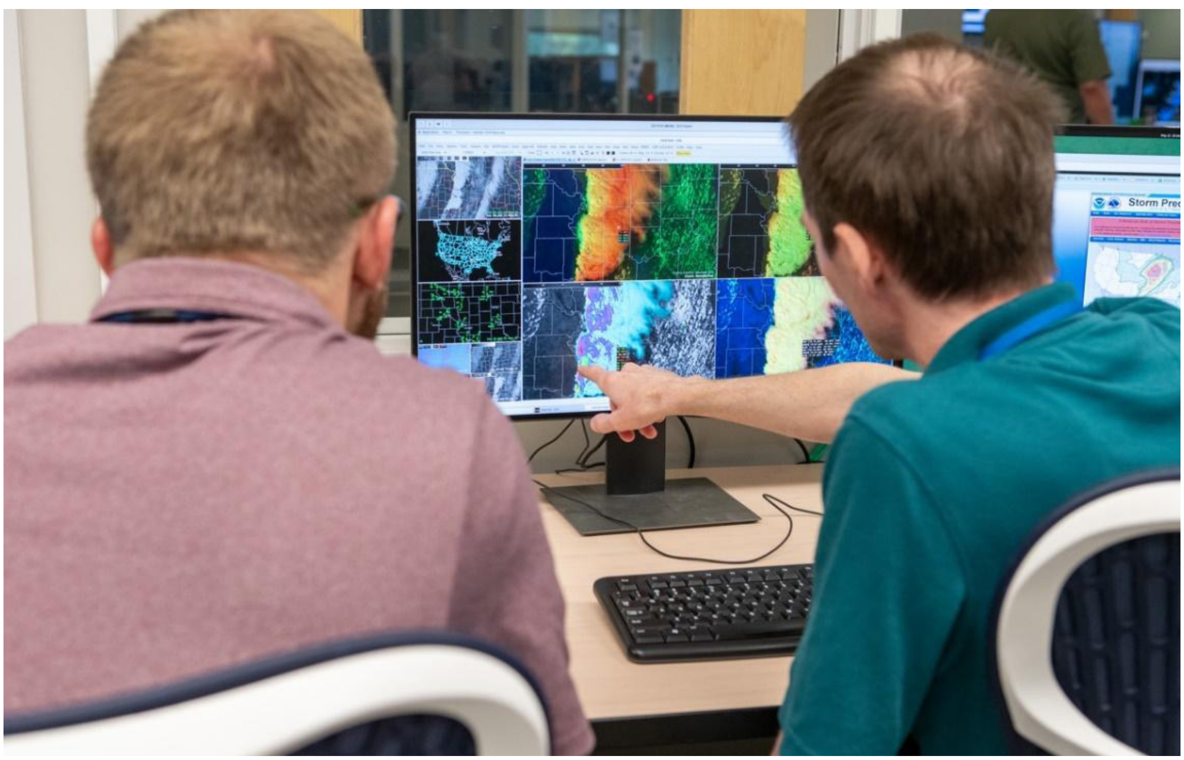


Photo 2-8: A NWS forecaster (right) points to a feature in an experimental cloud-top wind product while providing feedback to a developer (left) in the 2024 Satellite Convective Applications Experiment during a live severe weather event.

CIWRO Themes: Forecast Application Improvements
CIWRO Contributors: Steven Martinaitis, Melissa Wagner, Elizabeth Tirone, Dominic Candela, Chris Spannagle, Alyssa Woodward, Jessica Blair, Lexy Elizalde-Garcia, Michael Lowe, Ryan Pajela, Stephanie Edwards
Project Title: Exploring the Relationship Between FFSI and FLASH Using Detailed Flash Flood Surveys
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to map and predict the severity of flash floods as well as communication for high-impact weather events.

The NWS is evaluating a new means of rating the severity of the impacts from flash flooding with a new classification scale called the Flash Flood Severity Index (FFSI). While initially designed as a post-even analysis tool, the application of FFSI with flash flood reports can be used to design applications and guidance on how to predict the potential severity of flash floods. The premise of this research is to provide a detailed mapping of flash flood impacts, assigning each impact with a FFSI classification and associated NWS impact-based warning (IBW) tag, and then compare the findings to the hydrometeorological output generated within the Flooded Locations and Simulated Hydrographs (FLASH) system. This study conducted six flash flood surveys during the spring and summer months of 2024. These surveys utilized various data collection methods, including ground surveys, imagery from high-resolution satellite taskings and UAS, social and local media reports, and information from emergency managers and other local officials. Collaborative work with UMass-Amherst and NCAR were used to also collect societal surveys and traffic mobility data, respectively. Ongoing evaluations of the data have shown a correlation with FFSI values and unit streamflow values from hydrologic models. This will allow for future development and guidance on how to model flash flood severity that can be utilized in NWS operations. Moreover, several lessons were learned from surveying flash floods as well as identifying key features using high-resolution satellite and UAS data. This work has resulted in five conference presentations with plans for three journal articles.

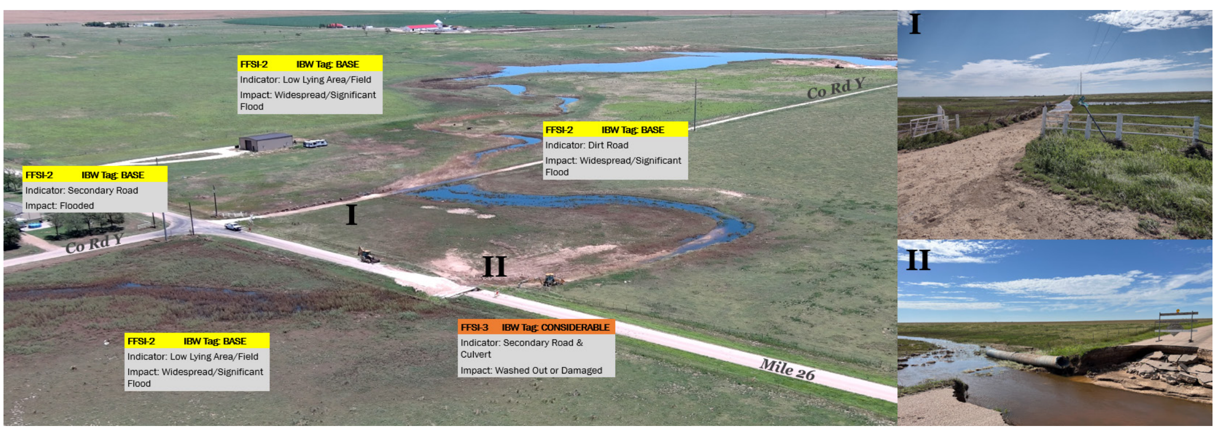


Photo 2-9: UAS imagery of the flash flood impacts near County Road Y and Mile 26 outside of Goodwell, OK from the flash flood event on 19 June 2024. Associated with this are ground surveys images of (I) the flash flood along the dirt road County Road Y and (II) the wash out of the road and culvert on Mile 26. Each impact is labeled with a FFSI classification, associated IBW tag, and impact indicator, and the degree of impact based on the FFSI classification tables.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Patrick Campbell, Pat Hyland, Jonny Madden, Justin Monroe, Claire Satrio, Rebecca Steeves
Project Title: HWT systems and data support
Relevance to NOAA: This project supports the NOAA mission by developing next-generation observational capabilities, incorporating social-science principles in new technology/training, and supporting the transition of infrastructure to cloud-based platforms.

The HWT provides evaluation of new meteorological insights and technologies across CIWRO and the NSSL, accelerating the transition of forecast and warning advances to operations. Since Oct. 2021, critical technological support provided to HWT experiments has included development of cloud technology, generation of archived case data, and continuous development of HWT systems and software to match required standards. New Advanced Weather Interactive Processing System (AWIPS) plugins have been developed to ingest and visualize experimental data from Phased-Array Radar, the New Mesoscale Detection Algorithm (NMDA), the Tornado Probability Algorithm (TORP), Probabilistic Hazard Information (PHI), Single Radar AzShear, and Single Radar DivShear. Other new experimental products integrated into AWIPS include GOES Radar Estimation via Machine Learning to Inform NWP (GREMLIN) and GLM Data Quality. Publications that reference HWT supporting technology include analysis of feedback from broadcast meteorologists (Obermeier et al. 2023) and new tornado detection algorithms (Sandmæl et al. 2023). Tangible outcomes from this project have included 2 journal articles, 18 conference presentations, 1 technology transfer, and 16 testbed evaluations across 48 operational weeks (22 weeks virtual, 26 in-person). These experiments involved 298 forecasters, 120 emergency managers, 45 broadcast meteorologists, and 8 members of the public who co-created experimental tools and products in the HWT. External partners involved in this project include the NSSL, SPC, OU IPPRA, Global Systems Laboratory, Colorado State CIRA, NWS WDTD, NWS Southern Region, NWS Eastern Region, and the NESDIS JPSS/GOES-R Proving Ground.

Photo 2-10: Technological support (foreground) for HWT operations during the spring 2024 Radar Convective Applications experiment.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Patrick Campbell, Jonny Madden, Justin Monroe, Claire Satrio, Rebecca Steeves
Project Title: Watch-to-warning research
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events and developing reliable probabilistic guidance products.

Watch-to-Warning research aims to discover new decision support products that provide probabilistic, rapidly updating hazard information during the current gap between severe weather watch and warning issuance. Now in its third year and carried out in conjunction with the Warn-on-Forecast (WoFS) team in CIWRO, this research has yielded new potential products which could increase warning effectiveness and lead time. Novel concepts evaluated during six weeks of HWT experiments in 2023 and 2024 included relatively short, adaptable watches focused on providing two hours of lead time, mesoscale and local discussions ahead of and between watches and warnings, and a new blended machine learning algorithm that combined storm-scale observational data with guidance from the WoFS system. These concepts were integrated into prototype cloud-based tools and platforms which were used to create and distribute experimental products across forecasters from different organizations. Storm-based Probabilistic Hazard Information (PHI) based on first guess guidance from machine learning algorithms was used to fill gaps between watches and warnings. Communications with partners including emergency managers were also investigated, with new communications templates arising from the experiment. Tangible outcomes from this project include 3 conference presentations and 2 testbed evaluations. Feedback from the 18 WFO forecasters and 11 SPC forecasters who participated in the HWT experiments has led to iterative improvements in storm-based probabilistic hazard research, as well as guidance for which concepts might successfully progress towards operations. External partners involved in this project include the NSSL, SPC, and the NWS.

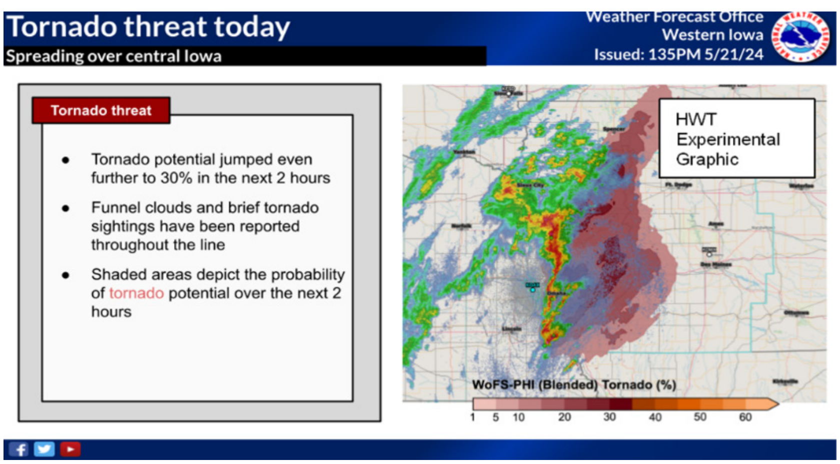


Figure 2-178: Experimental communication graphic created during an HWT evaluation showing hazard potential between the watch and warning timescales. Shown is the tornado threat over the next two hours (red shading) where darker shades indicate higher probability of tornado strike.

CIWRO Themes: Forecast Application Improvements, Weather Radar and Observations, Social and Socioeconomic Impacts of High-Impact Weather Systems
CIWRO Contributors: Terry Schuur, Kristofer Tuftedal, Jami Boettcher, Emily Blumenaur
Project Title: PAR HWT
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the RadarNext program, improving observation quality, incorporating social-science principles in new technology, and developing next-generation observational capabilities.

To better understand how forecasters may use a future operational phased-array radar (PAR) and how they would like these radars to operate, we have begun holding PAR HWT activities, the first of which being in August 2024. We bring forecasters in from around the country and have them work cases with ATD data and with conventional radar data in an attempt to parse what features are necessary for a future radar network, what is and is not necessary when it comes to volume scanning (i.e., whether faster updates are truly beneficial to the warning decision process), and ways that we can better use the ATD moving forward. Forecasters work multiple cases per day, fill out surveys after each case, and discuss their thoughts about ATD, the current radar network, and generally what they thought about using PAR data after completing each survey and at the end of the week. This work has already informed new scan designs for our Spring 2025 data collection efforts by informing us what aspects of radar data are most important to them within the warning decision process. This effort has resulted in three conference presentations.

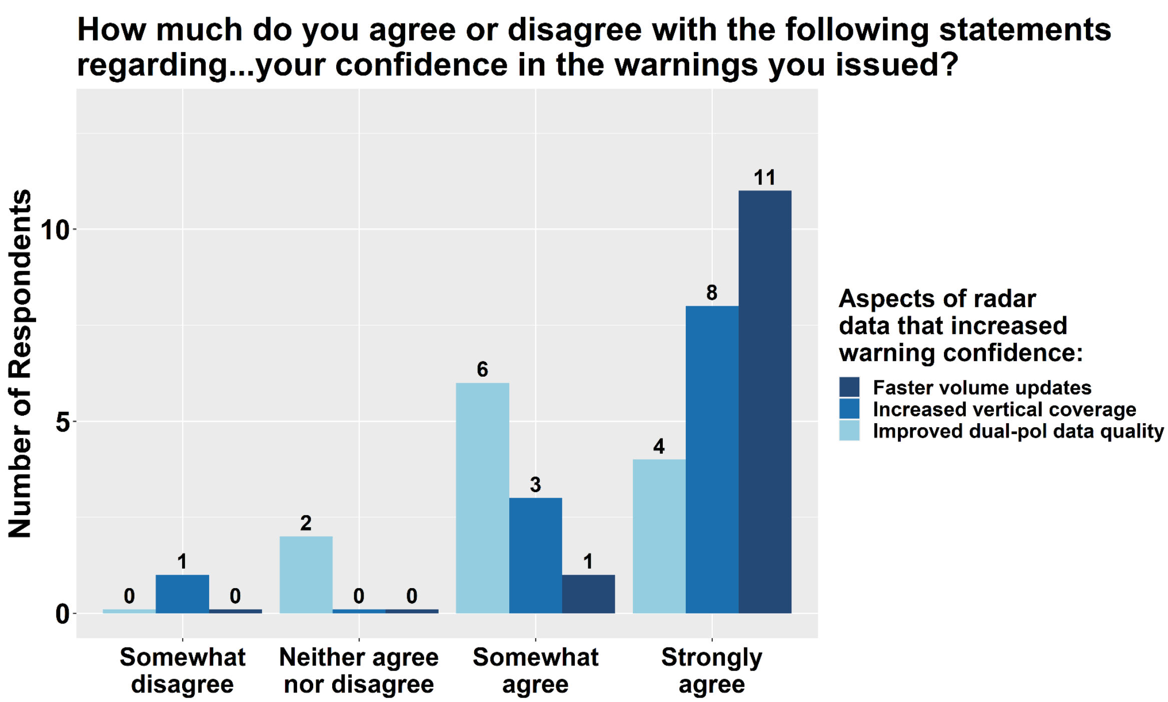


Figure 2-179: Bar plots showing responses to a question asked during the end-of-week surveys about how ATD data affected their warning confidence. The number above each bar represents the number of respondents for a given aspect considered.

CIWRO Themes: Forecast Application Improvements, Mesoscale and Stormscale Modeling
CIWRO Contributors: Patrick Skinner, Brian Matilla, Kent Knopfmeier, Monte Flora, Joshua Martin, Thomas Jones, Nusrat Yussouf, Miranda Silcott
Project Title: Efficient research-to-operations-to-research using real-time WoFS guidance
Relevance to NOAA: This project supports the NOAA mission by developing reliable probabilistic guidance products, improving weather and water predictions, creating/improving a trusted analysis of record for model verification/nowcasting, and informing operational forecast products that protect life and property.

Over 200 real-time WoFS runs have been performed since 2021. These forecasts are typically issued every 30 minutes between 17 and 03 UTC, with over 200 guidance products provided at 5-minute temporal evolution out to six hours of lead time. A full 6-hour WoFS forecast provides NWS meteorologists with probabilistic, short-term thunderstorm guidance with less latency and greater temporal resolution than any other real-time prediction system. Real-time interactions between NWS meteorologists and WoFS developers have accelerated adoption and mastery of NWS use of WoFS for real-time forecasting and have identified strengths and limitations of WoFS guidance, providing developers with paths toward improving forecast quality. WoFS developers have engaged more than 70 NWS offices through the real-time chatroom and remote presentations. Additionally, WoFS runs have been used for 10 testbed experiments and collaboration with external partners at SPC, WPC, GSL, AWC, and several universities. Tangible outcomes include 6 journal articles, over 20 conference presentations, over 10 training webinars, and direct contributions to issuance of over 100 operational severe weather forecast products that protect life and property.

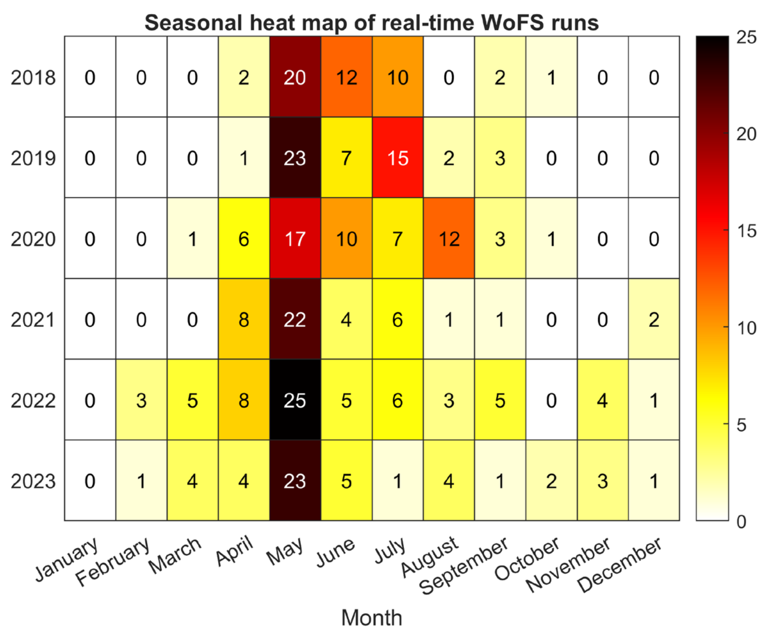


Figure 2-180: A heatmap of WoFS real-time runs per month between January 2018 – October 2023. Highlighting emphasis on the convective warm-season, with little sampling of September to March (i.e., cool-season)."

CIWRO Themes: Forecast Application Improvements, Social and Socioeconomic Impacts of High-Impact Weather Systems
CIWRO Contributors: Miranda Silcott, Kent Knopfmeier, Joshua Martin, Brian Matilla, Patrick Skinner, Katie Wilson
Project Title: WoFS real-world weather support experiments
Relevance to NOAA: This project supports the NOAA mission by incorporating social-science principles in new/technology/training and improving continuous engagement with partners

This project is an ongoing effort to run WoFS in real-time with various national centers and local weather forecasting offices to support the idea of WoFS to be transitioned into operational use. Recently, the SPC-funded cloud-based WoFS (cb-WoFS) to prioritize real-time runs during the cool-season aiming to enhance access to WoFS for a "Concept of Operations" while also achieving the scientific goal of studying WoFS performance during cool-season events in the 2023-2024 year. Additionally, the Aviation Weather Center (AWC) and NSSL jointly hosted to study the application of WoFS to aviation forecast problems, identify strengths and weaknesses, and recommend new forecasts products. These real-time experiments reveal how different national centers and local forecast offices may integrate WoFS into their operations and workflows for a variety of NWS products and hazards. This effort has been ongoing in relevant real-time settings since 2017 and has aided in many changes to products for optimizing usage for operational use (Burke et al., 2022, Gallo et al., 2022, Skinner et al., 2023a, Wilson et al. 2023., Wilson et al., 2024). Tangible outcomes from this project include 2 formal articles (upcoming), 3 conference presentations (upcoming), and 2 testbed evaluations/experiments (completed). External partners involved in this project include the SPC and the Aviation Weather Center (AWC).

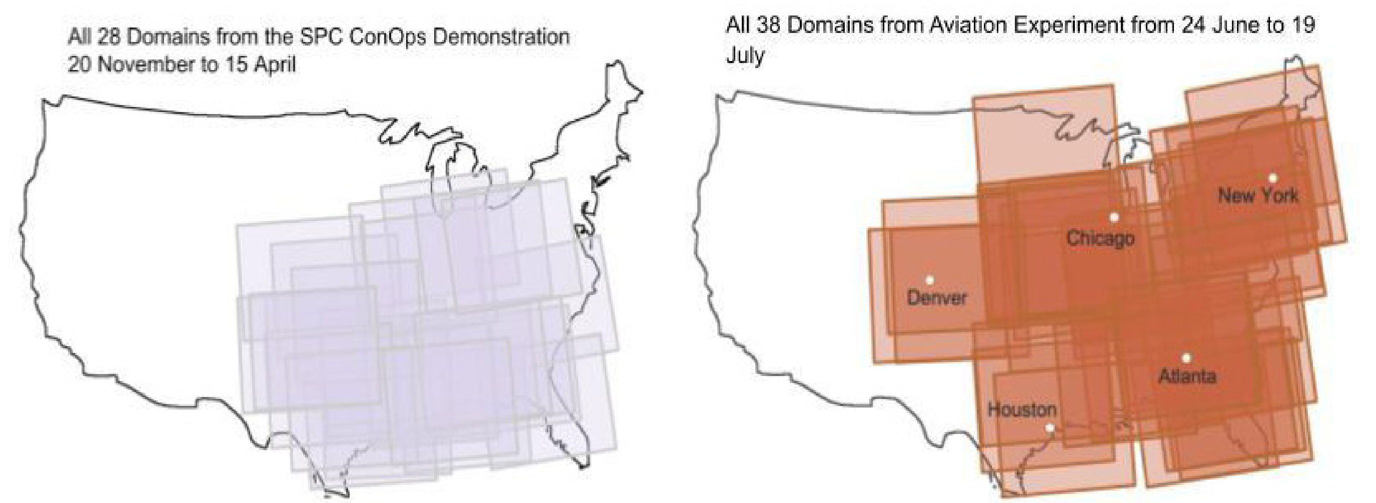


Figure 2-181: An illustration of the placement of all 28 WoFS domains during the 2023-2024 WoFS Concept of Operations demonstration funded by SPC (left) and the 38 WoFS domains runs across 19 days as part of the WoFS Aviation Experiment hosted by AWC and NSSL (right).

CIWRO Theme: Forecast Application Improvements
CIWRO Contributor: Andrew Wade
Project Title: Evaluating hourly-updating HREF-HRRR guidance blends
Relevance to NOAA: This project supports the NOAA mission by developing reliable probabilistic guidance products.

Forecasters use two primary forms of convection-allowing model guidance: the High-Resolution Ensemble Forecast (HREF) system and the High-Resolution Rapid Refresh (HRRR). The former represents a wider range of outcomes via diversity in model cores and physics, but only runs twice a day; the latter model updates hourly and incorporates newer observations. This project evaluated relative skill of longer-lead HREF guidance, shorter-lead HRRR guidance, and hourly-updating blends of the two. For the 2021 HWT Spring Forecasting Experiment (SFE), six pseudo-ensembles were formulated: the 12 UTC HREF; the 12, 15, and 18 UTC time-lagged HRRR (HRRR-TL) consisting of the four most recent HRRR runs; and two blends of 12 UTC HREF and 18 UTC HRRR-TL members. The first blend was weighted by the lead time of the members at each forecast hour. The second blend was weighted by members' near-surface temperature, dewpoint, and wind errors at 18 UTC compared to Real-Time Mesoscale Analysis (RTMA). Forecasts of updraft helicity and 40+ dBZ reflectivity were evaluated. Skill scores and SFE participants' ratings agreed that 12 UTC HREF guidance was superior to newer HRRR-TL guidance. 18 UTC blends outperformed 18 UTC HRRR-TL, but were similar in skill to 12 UTC HREF. Further analysis suggested by SFE comments disproved a speculated low/late bias in convective initiation in HRRR version 4. Findings were published in Weather and Forecasting by Wade and Jirak (2022) and presented internally to the SPC. SFE evaluation of these products involved SPC and NSSL collaboration.

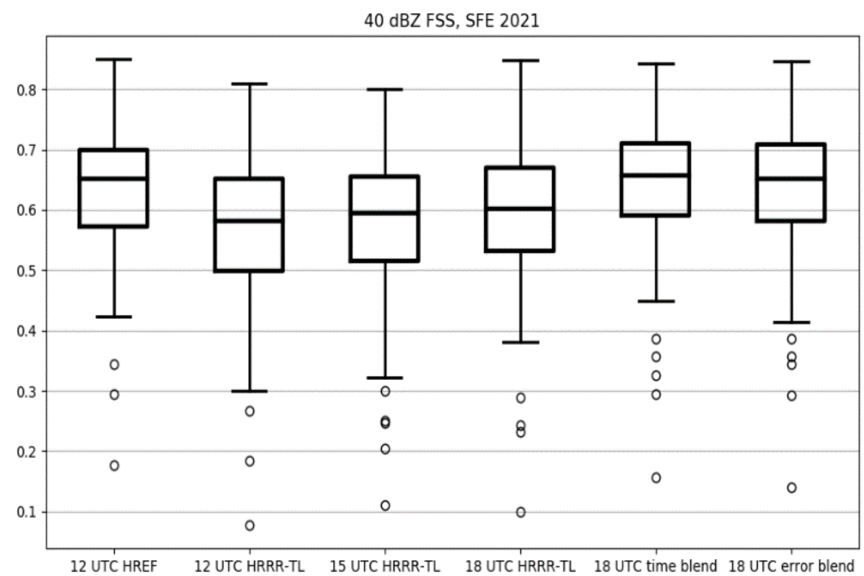


Figure 2-182: Boxplots of fractions skill score of neighborhood maximum ensemble probabilities of 40 dBZ model reflectivity, for the six guidance products evaluated: 12 UTC HREF, 12/15/18 UTC time-lagged HRRR, and two techniques for blending the 12 UTC HREF with the 18 UTC HRRR-TL.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Alyssa Bates, Samantha Boyd, Jessica Bunker, Katy Christian, Stephanie Edwards, Lexy, Elizalde-Garcia, Jill Hardy, Melissa Lankin, Mike Lowe, Dale Morris, Ryan Pajela, Chris Spannagle, Raven Vasquez, Hannah Wells, Andrew Wood, Alyssa Woodward, Kevin Grempler, Sarah Borg
Project Title: Radar & applications course
Relevance to NOAA: This project supports the NOAA mission by improving observations quality, incorporating social-science principles into new technology/training, and supporting the transition of infrastructure to cloud-based platforms.

The NWS routinely hires new forecasters into their workforce. For the last 30 years, as part of their initial on-boarding process, operational forecasters in the NWS are signed up for the WDTD's Radar & Applications Course. This course consists of over 100 hours of training on radar principles, using operational NWS tools, the various radar products available for them to use, background meteorology of severe convection and flash flooding, and the process of issuing weather warnings. This course uses a blend of training methods including on-line lessons, cloud-based exercises, webinars, videos, and wraps up with a forty-hour workshop. The entire course is made up of over 150 learning objects with approximately 90 of them being produced (or updated) by CIWRO instructors since October 2021. During that time, 455 NWS forecasters have been trained through this course (~20% of the operational workforce) with 429 having attended the week-long workshop during that time. A portion of those workshop completions include the period of time during the COVID pandemic when these workshops were held remotely using cloud-based Weather Event Simulator (WES) instances. CIWRO staff were critical in getting this functionality up and running so the WDTD could continue training NWS forecasters during this time period. In this effort, CIWRO instructors partnered with their federal collaborators at WDTD to ensure that NWS forecasters had the operational training needed to maintain the core warning decision making skills to protect life and property.

Photo 2-11: During the workshop portion of the Radar & Applications Course, CIWRO instructors work with NWS forecasters on radar interpretation of storms and help them with the necessary steps to issue Severe Thunderstorm, Tornado, and Flash Flood Warnings in the WDTD Lab.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Alyssa Woodward, Andrew Wood, Christopher Spannagle, Jessica Bunker, Melissa Lamkin, Hannah Wells, Kevin Grempler, Stephen Corfidi, Stephanie Edwards, Dale Morris, Samantha Boyd.
Project Title: Warning operations course (WOC) - Winter
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions, developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, and incorporating social-science principles in new technology/training.

NWS forecasters provide a variety of products and services during winter weather events in order to protect life and property. The Warning Operations Course (WOC) Winter Track consists of approximately thirty hours of training material designed to improve the performance of NWS offices in issuing watches, warnings, and advisories during winter events. The WOC Winter course is a collaborative training effort between CIWRO, NWS' WDTD, and subject matter experts from NWS forecast offices, other divisions of CIWRO, University Corporation for Atmospheric Research's (UCAR) COMET program, and NOAA/NWS's Weather Prediction Center. The WOC Winter course utilizes a combination of distance-learning modules, videos, an annual forecast challenge, live interactive webinars, and a Weather Event Simulator (WES)-in-the-Cloud simulation for training. The course covers topics in nine different areas including conceptual models, forecasting hazards, physiographic systems, remote sensing of winter hazards, the forecast warning process, and winter weather impacts. The forecast challenge portion of this course has been facilitated and led by a CIWRO team member since 2021 and has had over 500 NWS participants since 2021.CIWRO team members have authored seventeen new lessons, updated eleven lessons, and began developing a new WES-in-the-Cloud simulation for FY 2025. Each instructional component for NWS employees is tracked by the WOC on-site facilitator using the NWS Learning Center. Since 2021, there have been 185 curriculum completions for WOC Winter.

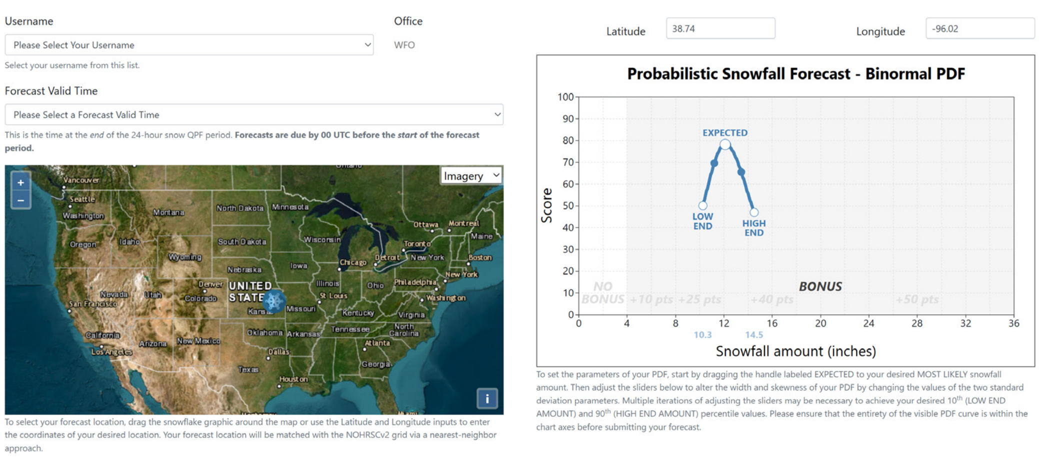


Figure 2-183: This is a screen capture from the WOC Winter Snowfall Forecast Challenge website. In this image, you can see how forecasters practice probabilistic snowfall forecasting.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Andrew Wood, Melissa Lamkin, Alyssa Woodward, Katy Christian
Project Title: Warning operations course (WOC) - flash flood
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

On average, flash floods cause the second highest number of weather-related fatalities across the United States and territories. As such, within the NWS, there is a critical need for training over how to best warn on and communicate flash flood hazards to the public. The flash flood warning operations course satisfies this need by providing NWS meteorologists and hydrologists with the latest tools and topics relevant to flash flood warning decision-making. This course, developed jointly by CIWRO and federal instructors, provides forecasters with 19 hours of online training materials that range from developing a conceptual meteorological framework for forecasting flash flooding to using tools to communicate the severity and impacts of flash flooding to the public. Given the wide range and depth of topic materials, CIWRO employees play a vital role in the development, maintenance, and support of this course. Of the 44 training modules within the flash flood course, CIWRO employees authored 21 of those modules. Since 2021, CIWRO employees have created 15 new training modules and significantly updated 5 modules. During the development of this training, CIWRO employees regularly collaborated with NWS offices to align training outcomes with operational needs. Additionally, CIWRO employees communicated with researchers from cooperative institutes and universities to ensure the latest science is incorporated. This cumulative effort is reflected in the 3200 NWS user completions of CIWRO authored lessons in the flash flood course since 2021.

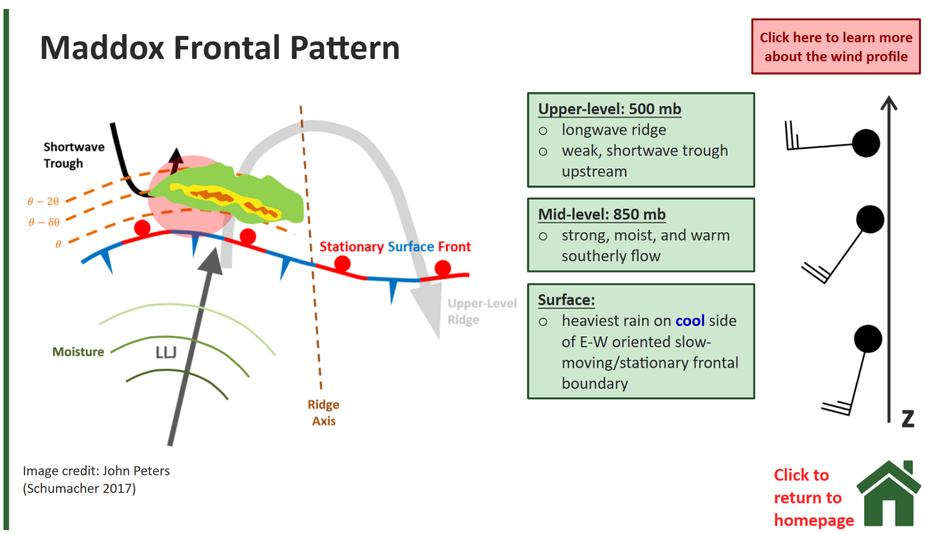


Figure 2-184: Images of training from the flash flood warning operations course highlighting forecasting flash flood events (left) to issuing the appropriate hydrologic product (right).

CIWRO Themes: Forecast Application Improvements
CIWRO Contributors: Hannah Wells, Christopher Spannagle, Melissa Lamkin, Stephanie Edwards, Jessica Bunker, Samantha Boyd, Michael Lowe, Sarah Borg, Alyssa Woodward, Alyssa Bates, Katy Christian, Stephen Corfidi, Kevin Grempler.
Project Title: Warning operations course (WOC) – severe
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions, developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, and incorporating social-science principles in new technology/training.

The Warning Operations Course (WOC) - Severe course consists of approximately twenty-six hours of training materials on the topic of severe weather. This course includes lessons and content that was developed in collaboration with external partners and subject matter experts from NWS forecast offices, other divisions of CIWRO, and NOAA/NWS's SPC. The course is designed to improve the performance of NWS offices in issuing severe thunderstorm and tornado warnings, with a target audience of NWS meteorologists. The course is broken into ten topics covering mesoanalysis, model-based information, storm structures and hazards, data fusion, warning methodology, verification, severe weather operations, the live instructor-led webinar, forecast challenge, and Weather Event Simulator (WES)-in-the-Cloud simulation. The WOC Severe course utilizes a combination of distance-learning modules, graded assignments, an annual forecast challenge with debrief webinars, instructor-led training webinars, and WES-in-the-Cloud simulations for training. Each instructional component for NWS employees is tracked by the WOC on-site facilitator using the NWS Learning Center. Since 2021, there have been 326 curriculum completions for WOC Severe. CIWRO team members have authored seventeen new lessons, updated ten lessons, graded over 250 hand analysis assignments, and helped create a new WES-in-the-Cloud simulation.

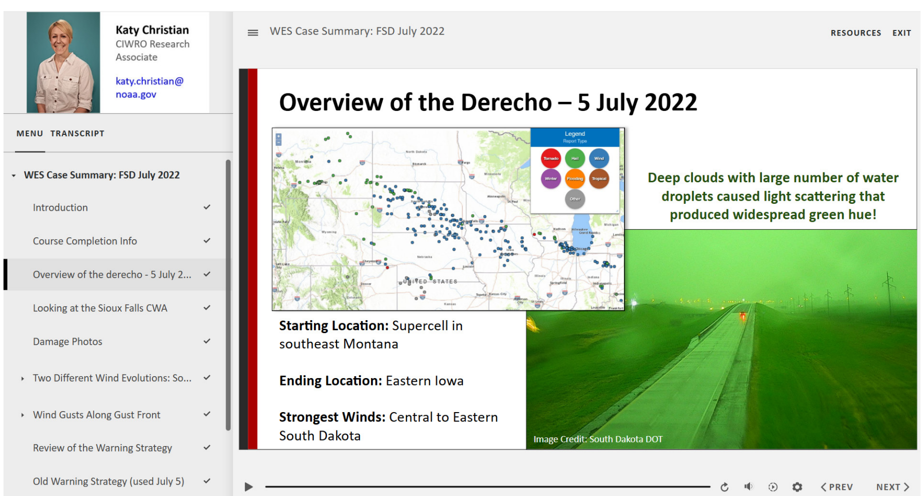


Figure 2-185: This screen capture from the WOC Severe WES Simulation case summary lesson shows the storm reports and other information about the event from the severe weather case used for the simulation.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Andrew Wood, Alyssa Woodward, Jessica Bunker, Melissa Lamkin, Christopher Spannagle, Ryan Pajela, Katy Christian, Hannah Wells, Dale Morris, Sarah Borg.
Project Title: Warning operations course (WOC) – human factors
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events and incorporating social-science principles in new technology/training.

The Warning Operations Course (WOC) Human Factors Track focuses on critical topics regarding the human element of warning decision-making, and this course has been facilitated and led by a CIWRO team member since August 2022. Many of the lessons and content in this course was developed through collaboration with external partners and subject matter experts from NWS Leadership Academy, OU's Institute for Public Policy, Research, and Analysis, and NSSL. The course offers instruction to improve the performance of NWS meteorologists, hydrologists and physical scientists who issue the assorted watches, warnings, and advisories at weather forecast offices. There are five different sections in the Human Factors Track covering the warning thought process, individual and team aspects of warning operations, engaging partners and the public, and tools for learning from experience. The WOC Human Factors modules utilize various learning technologies including videos, web-based training, graded assignments, and Weather Event Simulator (WES)-in-the-Cloud simulations. The course consists of approximately nine hours of training, and each instructional component for NWS forecasters is tracked by the WOC on-site facilitator using the NWS Learning Center. Since 2021, 617 NWS forecasters enrolled in the course from 127 different offices including local warning forecast offices (WFOs), Center Weather Service Units, and national centers. CIWRO team members authored 13 new lessons, significantly updated six other lessons, and graded over 300 user assignments in this time. Additionally, two conference presentations on new and updated course content were given.

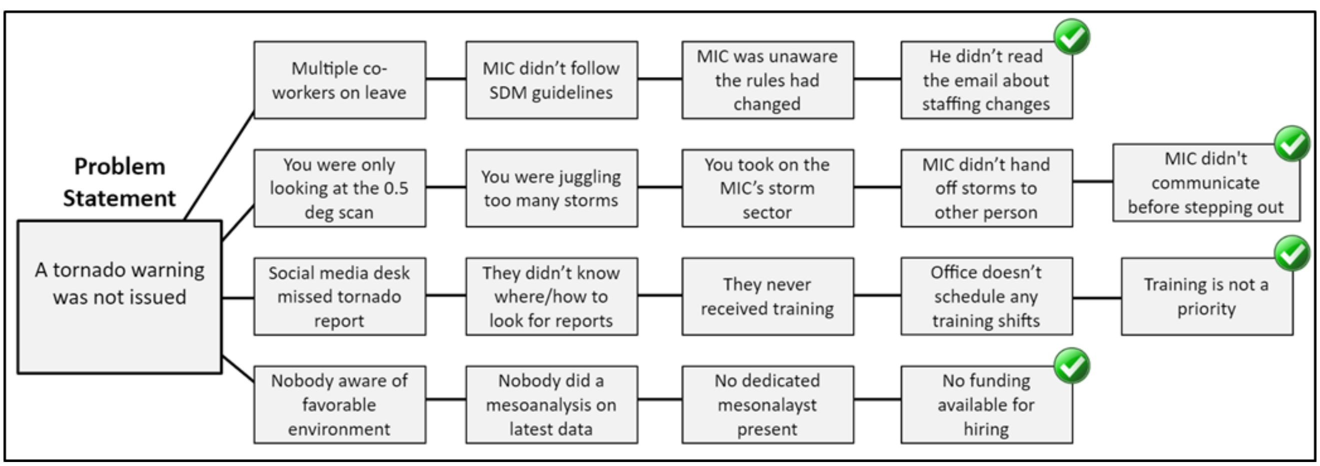


Figure 2-186: Screen capture of a Root Cause Analysis (RCA) assignment from the WOC Human Factors curriculum. In this image, you see that the problem statement reads "a tornado warning was not issued" followed by four branches outlining causal factors and root causes to the stated problem.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Chris Spannagle, Jill Hardy, Alyssa Bates, Mike Lowe, Jessica Bunker, Andy Wood, Melissa Lamkin, Raven Vasquez, Steve Corfidi, Katy Christian
Project Title: Storm of the month webinars
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, improving continuous engagement with partners, and incorporating social-science principles into new technology/training.

This project consists of an ongoing collaboration between CIWRO staff, WDTD federal instructors, NWS forecasters and various subject matter experts. This ongoing collaboration allows CIWRO staff to highlight both current operational best practices, as well as new procedures for experimental products planned for operational use. Since 2021 CIWRO staff has led 21 Storm of the Month webinars and were the sole content presenters of 5 of those sessions. Sessions led by CIWRO staff consisted of a wide range of topics from sidelobe contamination to derechos. CIWRO actively participates in knowledge transfer bi-directionally between the research and operational communities by seeking out presenters for presenting feedback on and facilitating these webinars. Additionally, CIWRO staff ensures that this knowledge is available to all NWS employees by recording, adding captions to and then uploading all webinars to YouTube. Since October 2021 over 1300 forecasters have registered for the live webinars, 340+ have completed watching recorded versions of the webinars via the Commerce Learning Center and over 3300 views of the webinars located on the Office of the Chief Learning Officer's YouTube page have taken place.

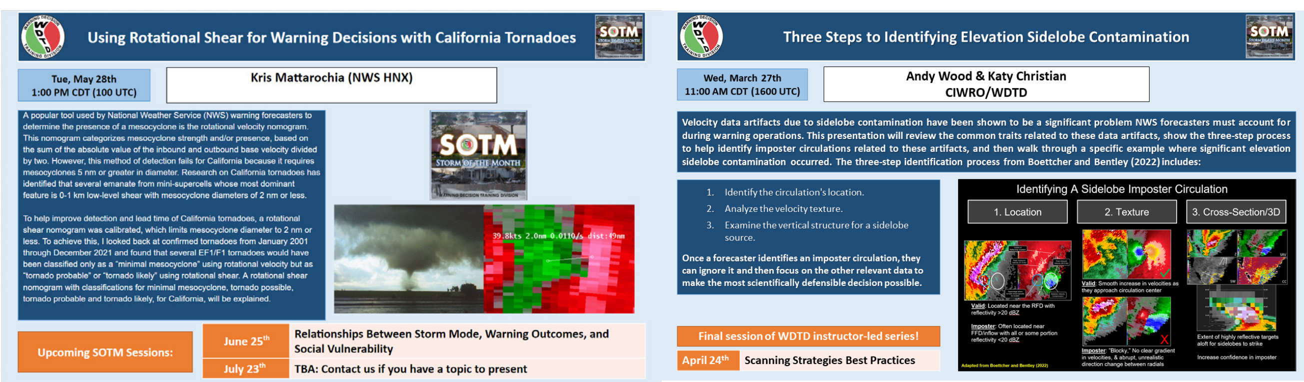


Figure 2-187: These graphics were created to advertise different Storm of the Month sessions.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Alyssa Bates, Jessica (Blair) Bunker, Lexy Elizalde-Garcia, Kevin Thiel, David Hogg, Patrick Skinner
Project Title: Research-to-operations and operations-to-research webinars
Relevance to NOAA: This project supports the NOAA mission by improving continuous engagement with partners and incorporating social-science principles in new technology/training

This project grew out of an existing partnership with NSSL, HWT, NWS, and CIWRO. The R2O/O2R Tales (ROOTs) webinar series raises awareness amongst NWS meteorologists of experimental tools and techniques that are being used to help issue short-fused (severe thunderstorm, tornado, and flash flood) warnings. CIWRO staff conceived all aspects of the ROOTS webinar series and facilitated on-site webinars for the HWT. Since October 2023, five ROOTs webinars have been orchestrated by CIWRO staff and a sixth is planned for early 2025. The live webinars reached roughly 175 individuals and the recordings on YouTube reached around 300 views. ROOTs presenters include operational meteorologists, researchers, cooperative institute scientists, and an emergency manager.

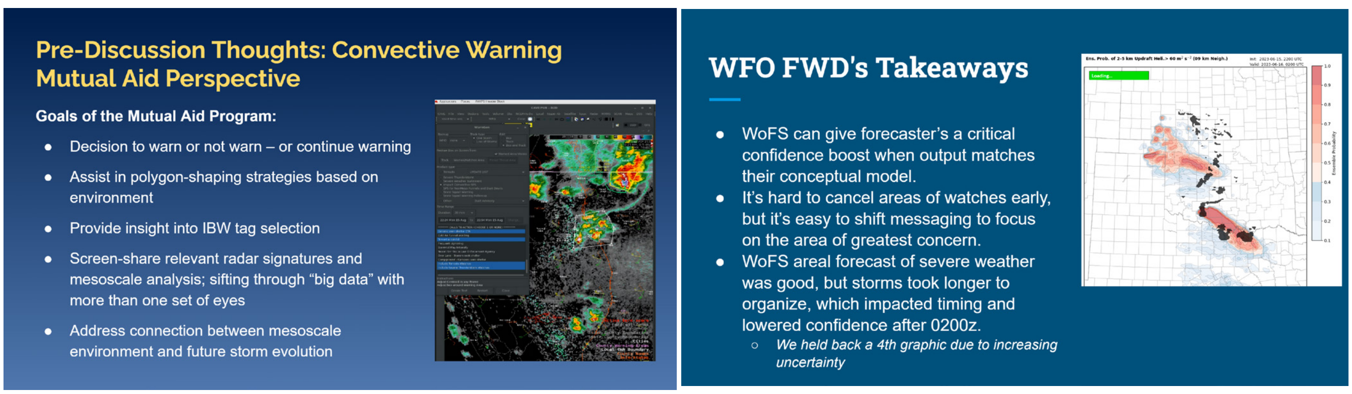


Figure 2-188: Left: Slide presented by Chauncy Schultz of NWS Bismarck as part of ROOTs webinar entitled "ROOTs: Mutual Aid for Convective Warnings: Current Experiences & Ideas for Future with TIM" on 4/4/2024. Right: Slide presented by Ted Ryan of NWS Fort Worth/Dallas as part of inaugural ROOTs webinar on 10/11/2023 entitled "ROOTs: Using WoFS to Enhance IDSS and Warning Operations on June 15, 2023".

CIWRO Themes: Forecast Application Improvements
CIWRO Contributors: Michael Lowe, Lexy Elizalde-Garcia, Raven Vasquez, Sarah Borg
Project Title: AWIPS build training
Relevance to NOAA: This project supports the NOAA mission by improving continuous engagement with partners and incorporating social-science principles in new technology/training.

The Advanced Weather Interactive Processing System (AWIPS) is the NWS software for data visualization, forecasting, and issuing warnings. When a new AWIPS build is released, CIWRO staff at the WDTD develop user training focused on the most significant AWIPS updates. This build training typically consists of a short video lesson and supplemental jobsheets for hands-on practice. The AWIPS build training enables NWS forecasters to incorporate the new functionality into their forecasting and warning operations. CIWRO staff collaborate with developers at Raytheon, the Global Systems Laboratory (GSL), and the Meteorological Development Laboratory (MDL) to identify key functionality for training and ensure accuracy in training content. Additionally, CIWRO instructors collaborate with other stakeholders at the AWIPS program and NWS beta test sites to refine the training products. CIWRO staff attend weekly stakeholder meetings, review development tickets, and communicate with developers and users to stay informed about upcoming changes and prepare training materials. Since October 2021, CIWRO staff have supported two full AWIPS build releases and one emergency release, producing one video and five jobsheets and updating the dedicated VLab build training webpage. The most recent build training video, released in January 2024, has been completed by 940 NWS employees via the Commerce Learning Center (CLC) with additional participation through non-CLC platforms.

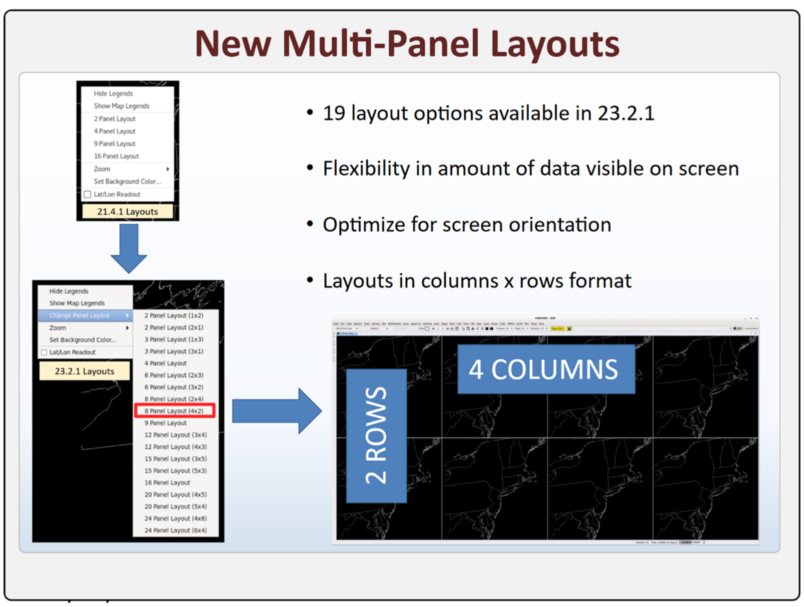


Figure 2-189: This is a screen capture from the 23.2.1 AWIPS build training video, released in January 2024, detailing the new AWIPS multi-panel layout options.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Michael Lowe, Samantha Boyd, Lexy Elizalde-Garcia, Raven Vasquez, Melissa Lamkin, Jake Sorber, Sarah Borg
Project Title: AWIPS fundamentals
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, incorporating social-science principles in new technology/training, and supporting the transition of infrastructure to cloud-based platforms.

The Advanced Weather Interactive Processing System (AWIPS) is the NWS's primary software for data visualization, forecasting, and issuing warnings. The WDTD developed AWIPS Fundamentals training as part of the required Radar & Applications Course (RAC), where new NWS forecasters learn to use AWIPS as applied to the course goal of radar interpretation and issuing convective weather warnings. AWIPS Fundamentals covers general usage, tools, and the Hazard Services warning generation software using an internet applet, jobsheets, and videos. Students practice in a simulated AWIPS environment via Cloud instances (WDTD, 2024). Since October 2021, CIWRO staff have managed AWIPS Fundamentals by maintaining and updating the content, tracking student progress for nearly 400 NWS forecasters from nearly all 122 Weather Forecast Offices (WFOs), nine Center Weather Service Units, and eight national centers, and providing technical support for over 500 student Cloud instances. These ongoing collaborations involve the new forecasters taking RAC and their local training facilitator. Currently, CIWRO staff are overhauling AWIPS Fundamentals into a standalone Fundamentals of AWIPS Course (FAC), separate from RAC, with new Cloud-based exercises using the latest AWIPS build and a redesigned applet repurposed as a refresher tool for all NWS employees. This new course will significantly reduce the wait time for new forecasters to start AWIPS training.

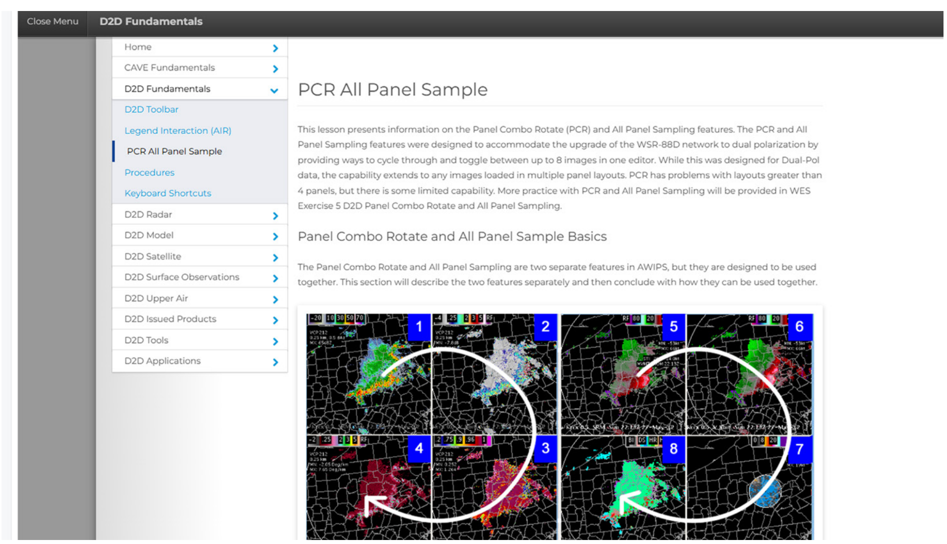
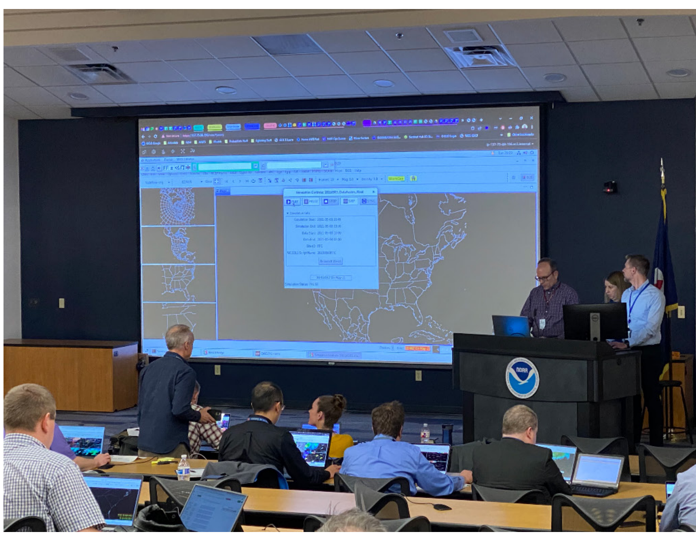


Figure 2-190: Screen capture of the current AWIPS Fundamentals internet applet, displaying a lesson covering the Panel Combo Rotate feature found in AWIPS.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Dale Morris, Melissa Lamkin, Jill Hardy.
Project Title: New NWS training officer (SOO/DOH) development course
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, incorporating social-science principles in new technology/training, and supporting the transition of infrastructure to cloud-based platforms.

NWS holds a training course for new Science and Operations Officers (SOOs) and Development and Operations Hydrologists (DOHs), who are the training officers at each field office. This "SOO-DOH Development Course" (SDC) is normally held every 2 to 3 years with a residence component at the NWS Training Center (NWSTC) in Kansas City. An internal NWS organizing committee plans the course content, which can vary significantly between each course offering. CIWRO staff contribute when invited. In 2022, CIWRO supported a forecasting exercise that was developed by the Forecast Decision Training Division (FDTD). This exercise was performed using a prototype WES (Weather Event Simulator)-in-the-Cloud capability, in a client-server environment where weather event data was hosted on a single server and multiple visualization clients were constructed "on-the-fly" for the participating forecasters, who each brought their own device, spread around the NWSTC auditorium. For this exercise, FDTD staff were on-site, while CIWRO staff worked behind the scenes to ensure the operability of the cloud technology. Another SDC was held in 2023 for a different cohort of training officers. In this version of the course, CIWRO staff participated on-site at NWSTC in a panel discussion about the transition from the physical WES to the Cloud-based WES. The course also provided opportunities for collaboration, networking, and learning for the CIWRO staff who were invited to specific sessions throughout the three-week course.




Photos 2-12 and 2-13: Photos from the August 2022 edition of the SDC. FDTD instructor Jason Jordan (at the podium) is starting the WES-in-the-Cloud simulation (left) while simulation participants use their own laptops to access the data in the simulation for analysis in the training exercise (right). Each participant manipulated their own individual meteorological data display inside a web browser that was synchronized to the main simulation in the cloud.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Andrew Wood, Stephanie Edwards, Kevin Grempler, Katy Christian
Project Title: Radar Operations Center (ROC) collaboration and WSR-88D build training
Relevance to NOAA: This project supports the NOAA mission by enhancing capabilities for the RadarNext program and/or WSR-88Ds and improving continuous engagement with partners.

This project consists of an ongoing collaboration between CIWRO, the WDTD, and the Radar Operations Center (ROC). The ROC manages and maintains the WSR-88D network of weather radar throughout the United States. They are responsible for providing periodic software and hardware updates to each radar system, and the WDTD's instructors train on those updates. CIWRO scientists participate in this process in several ways. They attend periodic meetings with the ROC to learn about significant changes occurring with the software updates. They get access to preliminary versions of the software, install the program, process and analyze radar data, make various screen captures for use in training, and provide feedback to WDTD instructors that can be included in the training for the radar update. Since October 2021, CIWRO staff participated in three cycles of radar build software and hardware updates. In addition to the tasks mentioned above, they provided other tangible benefits depending on what was needed at the time. For some builds, the CIWRO staff developed content that was included in the published training package. They also developed slides and participated in webinars facilitated by the ROC on forecaster use of the WSR-88D. This collaboration between the ROC, WDTD, and CIWRO is ongoing because of the tangible benefits to all parties and the agencies they serve. As of mid-December 2024, the three radar update training packages developed at WDTD in collaboration with CIWRO have resulted in over 2700 completions by NWS forecasters.

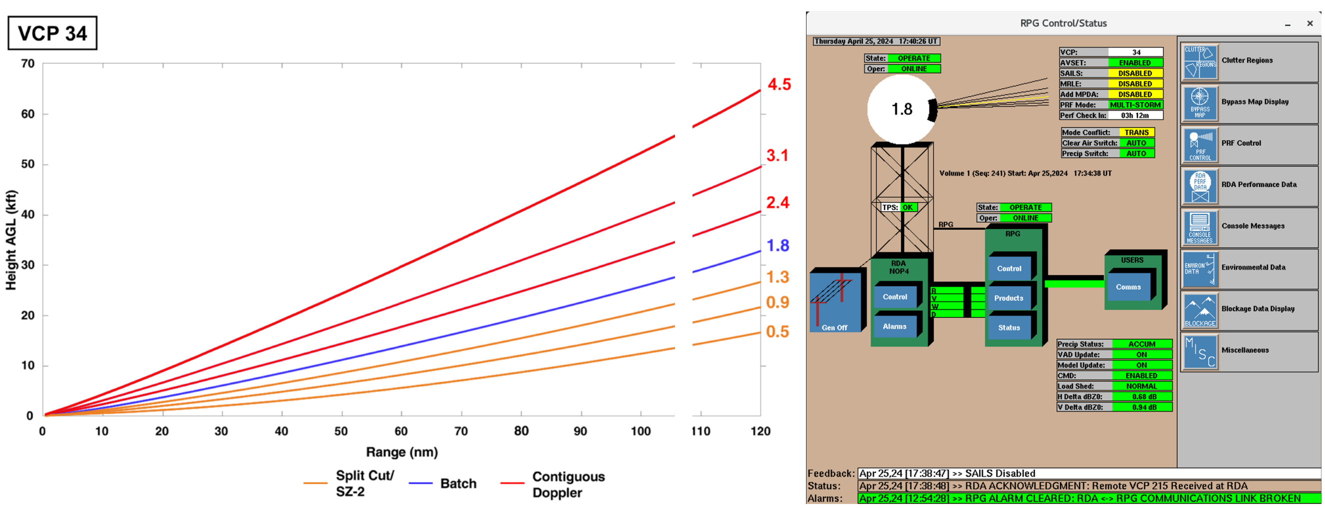


Figure 2-191: These graphics were created for WSR-88D software build update training. (Left) This chart shows the different elevation tilts included in the new volume coverage pattern 34. (Right) This graphic shows the software processing data collected using this new volume coverage pattern.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Samantha Boyd, Dale Morris, Jake Sorber
Project Title: Cloud automated scheduler (CLAS) for training activities
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, improving continuous engagement with partners, and supporting the transition of infrastructure to cloud-based platforms

The NWS WDTD in collaboration with CIWRO creates a variety of Cloud-based training activities for various aspects of the Advanced Weather Interactive Processing System (AWIPS). Because not all of these activities can be supported by the current Cloud-based Weather Event Simulator (WES), CIWRO created the Cloud Automatic Scheduler (CLAS) tool for forecasters to schedule and access training Cloud instances on-demand, available twenty-four hours a day. The system launches the disposable cloud instances at the scheduled time and terminates it at the end of the reservation. Each automated instance contains one training case, which reduces the overall size and cost; some instances can host up to 5 students at once, further reducing training costs. CIWRO developed all the scheduling, launching, and termination technology and software. CLAS has been released in multiple phases since 2022. The initial release allowed internal CIWRO and WDTD staff to use CLAS to support smaller training initiatives and make starting and stopping student cloud instances easier. A second release in early 2024 allowed for the first external use of CLAS by NWS forecasters taking entry level training, allowing training to be completed on demand. A third release (currently under development) will better support numerous NWS-wide training activities by providing the Cloud-based resources available to support up to 2200 forecasters launching instances across a training period of weeks to months. Since the initial deployment, CLAS has supported at least 2,625 individual and unique training instance requests.

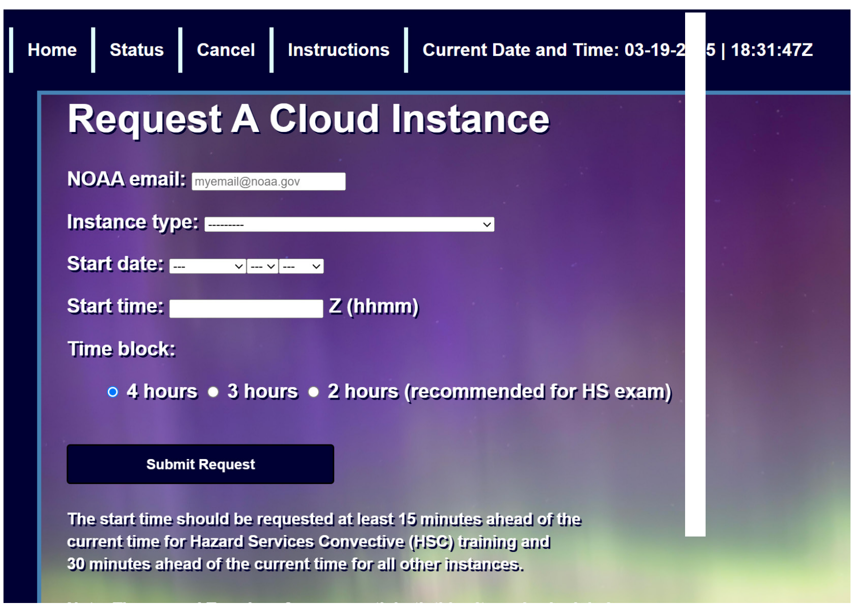


Figure 2-192: Screenshot of the Cloud Automatic Scheduler (CLAS) request form page, where users can select the cloud instance type, date, time, and length for their required training. Instances can be available for the user to access in as little as 15 minutes.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Dale Morris, Ryan Pajela
Project Title: AWIPS cloud archive of weather events for training and research
Relevance to NOAA: This project supports the NOAA mission by improving observation quality and/or stewardship and supporting the transition of infrastructure to cloud-based platforms

A functional Cloud-based Weather Event Simulator (WES) requires a corresponding archival system. CIWRO developed and maintains a 30-day rolling cloud-based archive of data from the Advanced Weather Interactive Processing System (AWIPS) to populate an ongoing case event repository. Prior to the NWS' retirement of their local archive systems, CIWRO guided local NWS staff to upload some 600 existing case events and simulations to the Cloud to form a National Case Library. These event types included severe convection, winter storms, fire weather, floods, dust storms, and tropical cyclones. Without CIWRO's intervention and guidance, these cases likely would have been lost. CIWRO also helped the NWS to deploy a simple method to upload small "case supplements" for perishable data that only exists within local AWIPS systems to merge with the 30-day archive. NWS staff uploaded nearly 20 supplements through the end of 2024. Through this work each local AWIPS automatically uploads current local AWIPS configuration data to the Cloud daily. Containing preferences, menus, derived products, and the like, these configurations ensure the Cloud WES maintains a similar look-and-feel to each office's operational system. CIWRO is designing and implementing a separate archive for the National Hurricane Center (NHC) to produce Tropical Cyclone Reports. Because of our expertise, NWS managers tasked us to create this archive, required for NHC to fully transition to AWIPS (a major NWS milestone), while considering their budgetary and operational constraints.

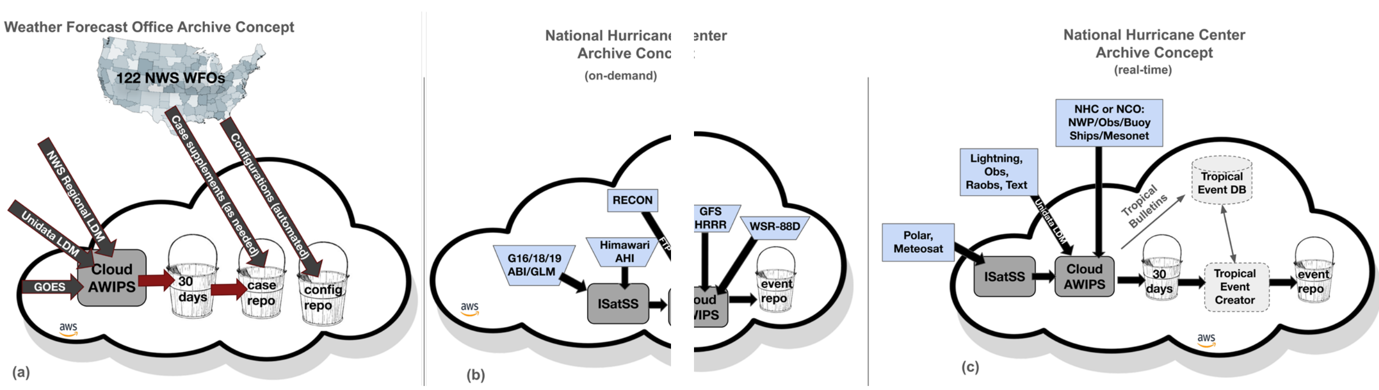


Figure 2-193: Conceptual schematics of Cloud-based archives for (a) Weather Forecast Offices (WFOs) and the NHC (b) on-demand component and (c) real-time component. The NHC on-demand concept utilizes datasets already present in the Cloud to the maximum extent possible to reduce costs (the WFO model adapted to NHC requirements could easily cost 20 times more). The real-time component aims to collect perishable data only available in real time (e.g., at NCEP Central Operations or NHC plus Polar and European geostationary satellite imagery). ISatSS is NOAA-developed product-generation software, supported by their "TOWR-S" team, that converts various satellite data sources into AWIPS-ready formats.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Dale Morris, David Creveling, Herve Kaffo, Stephanie Edwards, Ryan Pajela, Kevin Grempler
Project Title: Weather event simulator (WES) development
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, improving continuous engagement with partners, and supporting the transition of infrastructure to cloud-based platforms.

Ongoing improvements to the Weather Event Simulator (WES) included updates for compatibility with corresponding AWIPS (Advanced Weather Interactive Processing System) builds and deployment into Cloud computing environments. Updates included supporting Hazard Services (HS; the next-generation warning production tool within AWIPS used to issue hydrological watch/warning/advisory products) plus a major redesign of significant sections of the WES code. CIWRO deployed HS-compatibility into a Cloud version of WES for an upgrade to the RITC (RAC [Radar and Applications Course]-in-the-Cloud) in 2022 followed by in-person RAC workshops in WDTD's AWIPS Laboratory. The HS upgrade together with refreshed simulation cases and corresponding AWIPS configurations allowed RAC/RITC to maintain relevance to operational tools and to train 371 forecasters in issuing HS-based flash flood products since 2022. AWIPS code changes resulted in an incompatible archive data format that necessitated the code refactor which should be easier to maintain. The WES used in RITC required manual set-up and was not scalable to the entire NWS workforce, so CIWRO began designing an automated/scalable solution in 2023 while also supporting several prototype WES-in-the-Cloud demonstrations. NWS security requirements necessitated retiring the physical WES and archive hardware at each field office in June 2024, so CIWRO designed and deployed an interim Cloud WES (shared, field-controlled but CIWRO-configured) in January 2024 to support the most critical WES functions within NWS resource constraints. Only with CIWRO's work could the NWS workforce meet their own critical training requirements, such as completing nationally-deployed and locally-developed training simulations.

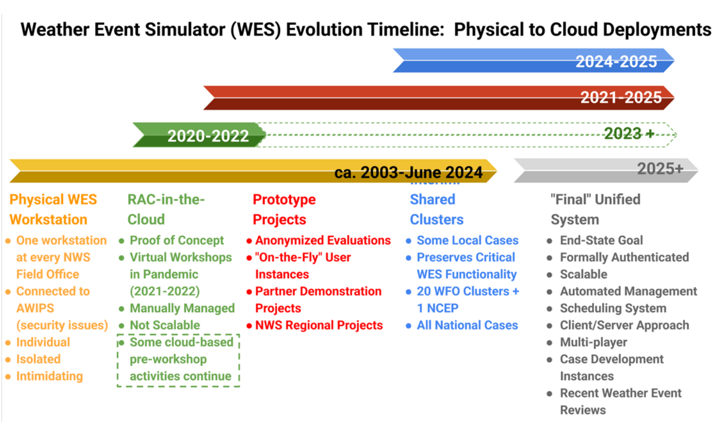


Figure 2-194: Overview of the transition of the Weather Event Simulator from physical, on-premise systems to Cloud computing deployments, including RAC-in-the-Cloud, several prototype projects, and the current interim, shared, cluster approach leading to an automated and scalable system.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Chris Spannagle, Kevin Grempler, Jill Hardy, Katy Christian
Project Title: Post-storm damage survey training
Relevance to NOAA: This project supports the NOAA mission by creating/improving a trusted analysis of record for model verification/nowcasting, optimizing platform-agnostic data and information and improving observation quality and/or stewardship.

This project consists of an ongoing collaboration between CIWRO, WDTD, and NWS. The NWS maintains the Damage Assessment Toolkit (DAT) which is an application used to both log and assign a rating to each damage point entered. NWS forecasters conducting damage surveys after significant weather events are the primary users of this tool. entered. As part of this project, CIWRO staff collaborates with its federal partners in order to gain expertise on the operational tools contained within the DAT as well as provide better job-centered training. The post-storm damage surveying course consists of 9 individual lessons on using the DAT that range from how to obtain access to the tool to how to use it to create tornado damage swaths and perform flash flood surveys. Since October 2021, CIWRO staff has authored or co-authored a majority of the lessons contained in this course and provided feedback and assistance in answering questions about the DAT. CIWRO is continuing to collaborate with the NWS and WDTD federal employees in regards to this course because of the tangible benefits to all parties and the agencies they serve. Updates to both the DAT and the background science are expected within the next 1-2 years with updates to the training expected after that time. As of mid-December 2024, the course has received over 5700 individual lesson completions by NWS forecasters.

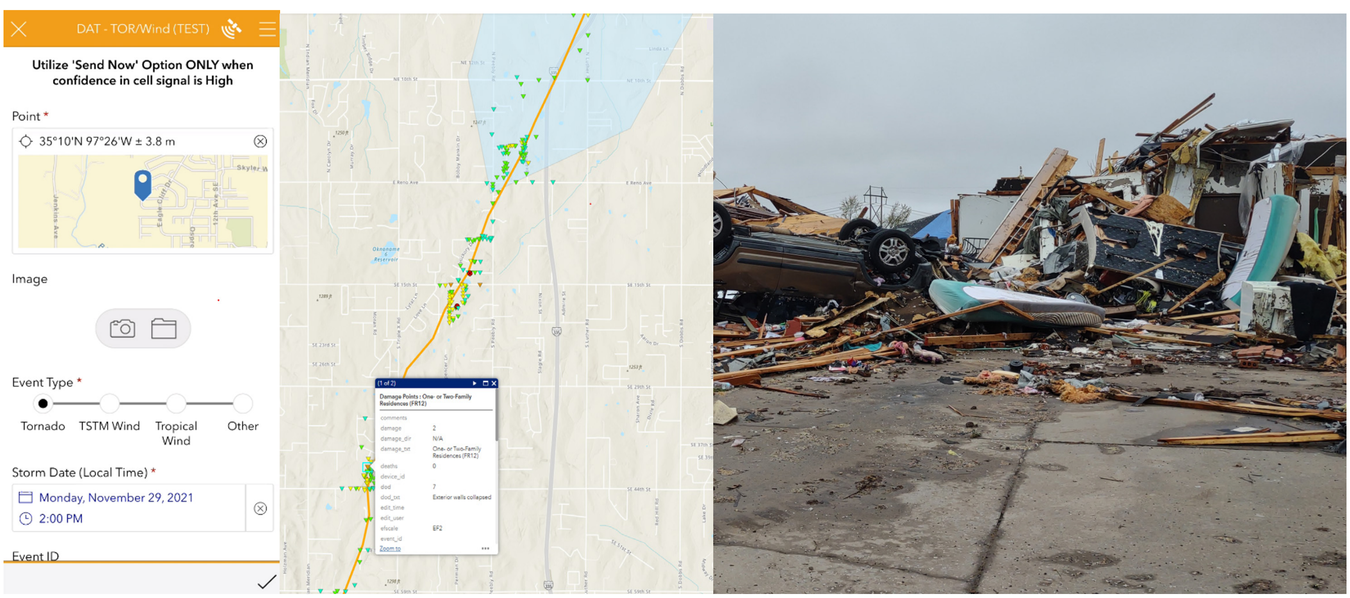


Figure 2-195: Examples of the DAT app (left), DAT points (center) and tornado damage (right)

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Edward Raven Vasquez, Lexy Elizalde-Garcia, Michael Lowe, Samantha Boyd, Sarah Borg, Jake Sorber.
Project Title: Hazard services warning generation tool training for NWS users and focal points
Relevance to NOAA: This project supports the NOAA mission by supporting the transition of infrastructure to cloud-based platforms, incorporating social-science principles in new technology/training, and developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

Hazard Services is software within the Advanced Weather Interactive Processing System (AWIPS) that is used by NWS forecasters to issue watches, warnings, and advisory products. CIWRO staff at the WDTD have learned and developed training on Hazard Services including modules, jobsheets, cloud instances, and reference sheets. In addition, our staff meet and converse regularly with developers at the Global Systems Laboratory (GSL), subject matter experts, and the NWS Forecast Decision Training Division (FDTD) on upcoming Hazard Services changes. When an update is released from the Hazard Services development team, WDTD staff refreshes past training and determines if additional material is needed. A NOAA-provided web service, called VLab, is used to host and distribute written training materials along with links to video (recorded) training on YouTube. In addition, CIWRO collaborate with other WDTD projects to incorporate Hazard Services into their curriculum and related training, or as support. For example, the Warning Operations Course for Winter hazards requires hands-on practice using Hazard Services to better prepare forecasters to issue cold-season products. In response, federal and CIWRO staff are collaborating to create an exercise on a real-world case in a cloud instance.

Hazard Services Roadmap

Phase 1	Phase 2	Phase 3	Phase 4	Outcome
Deploy Hazard Services with Common Alert Protocol, Hydro Hazsimp Limited testing of Hazard Services with Winter Wx hazards	Deploy Hazard Services with Non-Precip Wx (NPW) hazards and Winter Wx	Deploy Hazard Services with Convective, Partial County Alerting & Aviation hazards	Deploy Hazard Services with Fire Wx, NWEMs, Tropical & Long-Fused Marine hazards Fully integrate National Centers hazard generation via Hazard Services	Platform, tools enabling a dynamic collaborative forecast, hazard process across NWS WFOs, ROCs, & National Centers & that improves forecast consistency, accuracy

Figure 2-196: A roadmap of Hazard Services rollout phases. As of January 2025, Phase 2 is in the process of rolling out to the NWS.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Chris Spannagle, Kevin Grempler, Stephanie Edwards, Jessica Bunker, Samantha Boyd
Project Title: Forecast challenges
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events.

NWS forecasters can sometimes struggle forecasting severe and winter weather events when they perform these tasks infrequently. The Winter and Severe weather forecast challenges consist of an experiential learning activity allowing NWS forecasters to improve their winter and severe weather forecasting skills and the way they communicate anticipated threats. While only those enrolled in the Warning Operations Course for Severe and Winter are required to participate, annually more than five times that number choose to participate. Since October 2021, over 2200 NWS forecasters have participated in these challenges. Both challenges are entirely run by CIWRO staff. In both challenges participants issue 24-hour point forecasts for a location of their choosing within the continental United States (CONUS). Probabilistic snowfall forecasts are issued in the winter challenge and forecasts for a single type of severe weather in the severe challenge. All forecasts are required to include a discussion discussing their forecast reasoning and why they selected their forecast location. Forecasts, and their associated discussions, are then posted to a website shared among participating forecasters and instructors who give real-time feedback on the forecast quality and accuracy plus a score for each forecast. This approach allows NWS forecasters to learn about new techniques used by other forecasters and practice their own forecasting and communication skills on a daily basis. Additionally, because forecasters choose their forecast point, the challenges provide opportunities to improve and maintain severe and winter weather forecast skills, especially for duty locations that don't regularly experience severe convection.

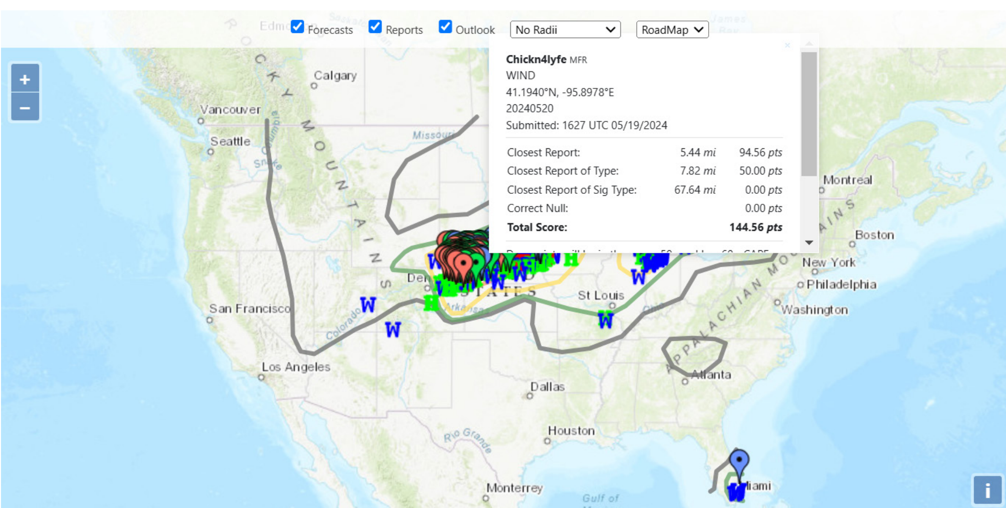


Figure 2-197: Results page from the severe forecast challenge with feedback displayed

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Ian Gesell, Matthew Paulus, Travis Enzensperger
Project Title: Probabilistic impact-based decision support services (IDSS) training and support
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events and developing reliable probabilistic guidance products.

The NWS has transitioned its products and services to place more of an emphasis on the societal impacts of weather events rather than just the simple facts of the forecast. They have also started delivering more forecast information in a probabilistic (versus a deterministic) manner. These efforts intertwined recently into a concept known as probabilistic impact-based decision support services. CIWRO staff have been collaborating with instructors at the Forecast Decision Training Division (FDTD) since before October 2021 to develop training on this subject. Early efforts focused around the Graphical Forecast Editor (GFE) tool which generates gridded forecast products disseminated to the public. CIWRO staff created job sheets for GFE focal points to share configuration best practices and help standardize configuration of this tool. After completing that effort in early 2023, CIWRO staff pivoted their efforts to forecaster interpretation of probabilistic information. They worked with FDTD instructors to develop a new course teaching forecasters the fundamentals of probabilistic forecast products. This course, titled Ensemble Fluency, was released in the summer of 2024, consists of 27 separate lessons, and is required for all NWS operational forecasters to complete. CIWRO staff contributed to this effort by identifying cases for the training, writing quiz questions on interpreting the data, and writing documentation to help local training facilitators. As of early January 2025, 1764 completions of the entire course have been recorded with several hundred other forecasters having completed a subset of the material. Work on this subject is on-going.

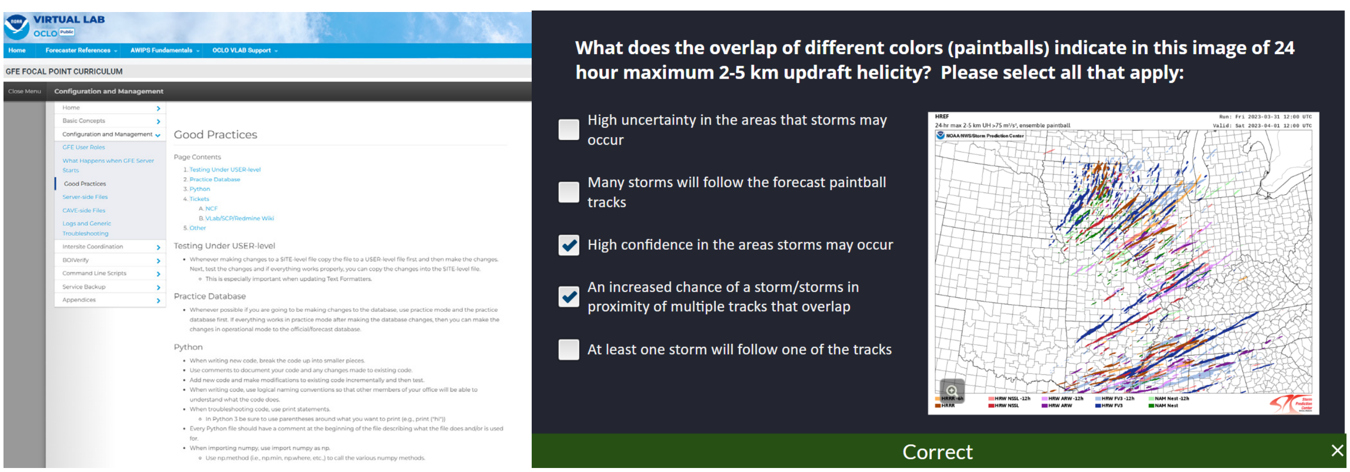


Figure 2-198: Images show examples of CIWRO instructor contributions for this project. On the left, a job sheet for GFE focal points shares best practices on template configuration. On the right, an example quiz question from one of the Ensemble Fluency lessons.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributors: Alyssa Bates, Samantha Boyd, Jessica Bunker, Katy Christian, Stephanie Edwards, Lexy, Elizalde-Garcia, Jill Hardy, Melissa Lankin, Mike Lowe, Dale Morris, Ryan Pajela, Chris Spannagle, Raven Vasquez, Hannah Wells, Andrew Wood, Alyssa Woodward, Kevin Grempler
Project Title: WDTD outreach activities
Relevance to NOAA: This project supports the NOAA mission by improving continuous engagement with partners.

CIWRO staff at WDTD routinely engage in numerous outreach activities involving NWS, academia, professional societies, the public, and school-age students. We work behind-the-scenes to support NWS offices in enhancing their own outreach using the CIWRO-developed WES (Weather Event Simulator)-in-the-Cloud simulator platform. The Baltimore/Washington office demonstrated warning operations to meteorologists on-site at every TV station in their forecast area. Staff from the Binghamton, NY NWS office exposed students and faculty at Cornell University to operational forecasting with WES-in-the-Cloud. For academia, we work directly with meteorology students at OU (guiding them through simulated NWS operations in our unique training lab), the University of North Dakota, and other institutions. CIWRO instructors publish all jointly developed content online on WDTD's website. Professional organizations like the American Meteorological Society and National Weather Association provide continuing education credit using these lessons. The online lessons are also used in a variety of additional professional and academic settings. Public outreach includes the National Weather Festival where we guide the public in issuing their own tornado warnings using our simulator software. We engage in a variety of after-school and summer camp opportunities featuring experiential activities for school-age children, introducing them to careers in operational and research meteorology. All these activities feature CIWRO's work while advancing the NWS mission of protecting life and property. Undoubtedly these efforts ensure CIWRO training materials reach a larger community than the primary intended audience of NWS forecasters.


Photo 2-14 and 2-15: CIWRO staff at WDTD participate both in outreach activities in traditional ways like the National Weather Festival (images on the left and middle) as well as in less traditional ways like supporting the use of CIWRO-developed tools in outreach events conducted by NWS forecasters (image on the right).

CIWRO Themes: Forecast Application Improvements
CIWRO Contributor: Jane Niemeyer
Project Title: NWSTC Support for NWS decision support and communication services
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions; developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events; and improving continuous engagement with partners

The NWSTC plays a crucial role in supporting IDSS Deployment and Tropical Boot Camp by conducting simulation-based courses that involve extensive coordination of personnel and resources. It trains NWS employees to effectively communicate with emergency managers, media, and community leaders while providing a safe environment for trial and error before deployment in real weather events. By preparing personnel for public-facing roles and enabling experts to teach the interpretation of tropical products and storm science, the NWSTC strengthens the NWS decision support mission. Collaborating closely with the National Hurricane Center, it helps alleviate the pressure of high-stakes tropical events, with 36 out of 48 Tropical Boot Camp trainees already contributing to real-world responses, including Hurricane Lee (2023) in Maine and Hurricane Hilary (2023) in California. Additionally, NWSTC has developed e-learning courses for Decision Support Training, completed by 400 employees as an essential first step toward deployment readiness, ensuring NWS personnel are equipped to serve their communities beyond the office.

Photo 2-16: During the Tropical Boot Camp, NWS participants practiced speaking at a mock press conference.

CIWRO Theme: Forecast Application Improvements
CIWRO Contributor: Jane Niemeyer
Project Title: NWSTC support for the NWS leadership academy
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions; developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events; and improving continuous engagement with partners

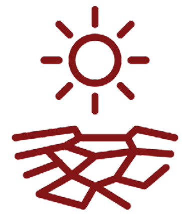
The NWSTC has been instrumental in supporting the NWS Foundations: Introductory Course for new hires by delivering a combination of webinars and a three-day residence course that provides resources, interpersonal training, and an understanding of NWS and NOAA policies and norms. It ensures content is optimized for virtual and live formats while inspiring employees to see themselves as leaders and integral members of the NWS mission. By helping participants grasp the broader scope of the NWS beyond their local offices, the course contributes to workforce retention, having engaged 1,109 participants—25% of the NWS—since 2020. Additionally, NWSTC has supported the Team Lead Development Course, which equips team leads and lead forecasters with skills in professional development, management, decision-making, conflict resolution, and coaching. Through networking opportunities and the establishment of a strong support system, this course fosters a positive organizational culture, fills an educational gap for scientists, and strengthens workforce retention by empowering participants to mentor and support their teams effectively.

Photo 2-17: Recently hired NWS employees gather to hear a speaker during the NWS Foundations course.

CIWRO Theme: Forecast Applications Improvements
CIWRO Contributors: Ming Xue, Nathan Snook, Jun Park, Marcus Johnson, Keith Brewster, Chengsi Liu, Andrew Berrington
Project Title: CAPS Contributions to Unified Forecast System Research-to-Operations Project (UFS-R2O)
Relevance to NOAA: This project supports the NOAA mission by contributing to the development of the next-generation operational Rapid Refresh Forecasting System (RRFS) Ensemble Forecast System (REFS), and the development and testing of radar and satellite lightning data assimilation capabilities within the JEDI framework.

Under the support for the NOAA UFS R2O project, the CAPS team worked on the development and optimization of RRFS ensemble employing multiple optimized physics suites with stochastic physics perturbations, and radar and lightning assimilation development for JEDI targeting for RRFS version 2. On developing optimized RRFS ensemble, CAPS evaluated many combinations of physics within the FV3-LAM configured based on prototype RRFS, and tested multi-physics configurations of the RRFS ensemble, and examined the impact of additional stochastic physics perturbations. The testing was first done for selected cases, then systematically tested and evaluated during a realtime HWT Spring Forecasting Experiment, and in Hydrometeorology Testbed (HMT) winter weather and summer Flash Flood and Intense Rainfall (FFaIR) forecast experiments. The findings were reported at annual R2O conferences during AMS Annual Meetings, and published in several referred papers (Supinie et al. 2022; Hu et al. 2023; Johnson et al. 2025; Snook et al. 2025). On developing radar and lightning DA capabilities with JEDI, CAPS implemented radar and lightning observation operators into the JEDI framework, and implemented their assimilation capabilities within JEDI LETKF and En3DVar. Initial test results using JEDI LETKF are published in Park et al. (2023). The JEDI LETKF was run in realtime during 2024 HMT FFaIR forecast experiment. The results were reported at 2025 AMS Annual Meeting (Xue et al. 2025; Park et al. 2025).

iv. Subseasonal-to-Seasonal (S2S) Prediction for Extreme Weather



This thematic line was introduced to CIWRO at the onset of our current award on October 1, 2021, making it a relatively new area of research. The work within this theme falls into two primary categories: tools and decision-support aids for the forecast process, and analyses of record that help improve understanding of temporal and spatial trends while providing broad-scale verification.

Several mature projects have established a strong foundation for further advancements in these areas. One of the key challenges in this field is developing methods to predict hazard likelihood at subseasonal-to-seasonal (S2S) time horizons, as S2S forecasts do not explicitly predict specific severe-weather hazards. CIWRO investigators have designed a customized decision-support system tailored to the needs of partners at the SPC, enabling them to assess the probability of various hazards. This system also provides retrospective verification and scoring of probabilistic forecasts at S2S time scales. Research efforts have also analyzed both conventional numerical weather prediction (NWP) models and the first generation of AI/ML models, offering an initial glimpse into which aspects of S2S forecasts may be useful for prediction and messaging, as well as identifying necessary improvements for future model iterations. Another key focus within this thematic line is the production of analyses of record. Decadal reanalyses featured in this section, along with similar analyses throughout this report, provide stakeholders with valuable data to better understand the temporal and spatial trends of severe-weather phenomena, including heavy rain, lightning, ice storms, and flash floods. These analyses serve as critical resources for decision-makers and forecasters in assessing past events and improving future forecasting capabilities. Several projects under the S2S umbrella are in their early stages and have yet to yield tangible outcomes. These include the development of object-based verification techniques for heavy snowstorms in the S2S time frame and beyond, the establishment of a new NOAA testbed category known as the Subseasonal Severe Weather Forecasting Experiment, the advancement of analyses of record for ice, snow, and liquid-equivalent precipitation using gauge observations and crowd-sourced observer networks, and the application of machine learning to develop improved storm hazard analysis.

Over the next five years, planned activities will focus on developing impact frameworks to scale hazards, allowing for better anticipation of events that require advanced planning and preparation at the beginning of a season. Additionally, efforts will be made to extend the SPC's hazardous weather outlook to two weeks, further enhancing the ability to forecast and mitigate the risks associated with severe weather events.

CIWRO Themes: Subseasonal-to-Seasonal Prediction for Extreme Weather, Forecast Application Improvements
CIWRO Contributors: Kimberly Hoogewind, Eric Loken, Michael Hosek
Project Title: Developing day 1–15 machine learning severe weather guidance from GEFSv12
Relevance to NOAA: This project supports the NOAA mission by developing reliable probabilistic guidance products and improving weather and water predictions.

A primary goal of the FACETs framework is to provide probabilistic hazard guidance across a continuum of time and space scales. Much of FACETs research in regard to severe convective storms has focused on the shorter end of the time spectrum (e.g., 0–6 hours), but the concept naturally extends to the medium-range and subseasonal-to-seasonal (2 weeks to 3+ months) timescales. A machine-learning (ML) approach is well-suited for severe weather forecasting applications as numerical weather prediction (NWP) models do not explicitly predict hazards (i.e., hail, tornadoes, and severe wind gusts). Environmental predictors from an ensemble global NWP system were used to train a ML model to produce severe weather probabilities. While NWP skill tends to drop off sharply beyond week 1 (Berrington et al. 2024), the ML guidance has been shown to produce skillful and reliable severe weather probabilities at lead times of 1–15 days (Clark et al. 2025, *in review*). Tangible outcomes from this project include two evaluations within the HWT spring forecasting experiment, training provided to SPC forecasters, development of a web viewer for pseudo-operational forecasts with integrated verification overlays, development of a monitoring/verification product suite and web-based visualization, 3 conference presentations, 2 journal articles, and 1 algorithm ready for transition to NWS SPC operations. External partners involved in this project include NWS/SPC and OU School of Meteorology.

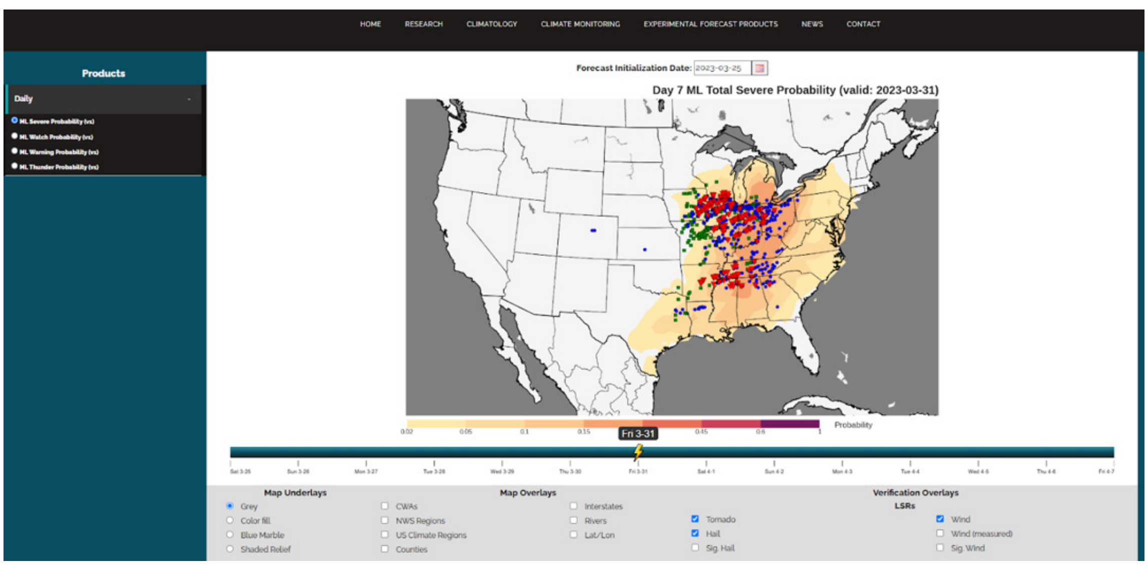


Figure 2-199: Web viewer for experimental day 1–15 ML severe weather forecast guidance (available at https://apps.nssl.noaa.gov/s2s-severe/forecast_gefs_ml.html).

CIWRO Themes: Subseasonal-to-Seasonal Prediction for Extreme Weather, Forecast Application Improvements
CIWRO Contributor: Allison Brannan
Project Title: Synoptic-based medium-range forecast skill of tornado outbreaks
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions

With a long-term goal of creating experimental sub-seasonal forecasts for tornado outbreaks, it must first be discovered if current operational models possess skill in predicting the synoptic-scale features present on tornado outbreak days at sub-seasonal lead times. This study utilized anomaly correlation coefficients to demonstrate the objective limit on the predictability of the 500 hPa geopotential height pattern on tornado outbreak days using reforecasts from the Global Ensemble Forecast System (GEFSv12). Using the ensemble mean averaged over 181 outbreak events between 2000-2019, GEFSv12 shows skill in forecasting 500 hPa heights extending out to 8 days of lead time. This is not suggesting that tornado outbreaks are necessarily predictable at this lead time, as this is only representative of the predictability of the synoptic-scale height pattern. This study discovered that while the predictability is not statistically significantly different based on the outbreak size or duration, there is evidence of greater predictive skill in the 500 hPa height pattern present on winter-time tornado outbreak days compared to the other seasons. Tangible outcomes of this work include 3 conference presentations. This work involved external collaboration with NSSL, the Atlantic Oceanographic and Meteorological Laboratory, the NOAA Unified Forecast System Subseasonal to Seasonal (S2S) Application Team, and the NOAA Environmental Modeling Center Coupled Modeling Team focused on Coupled Global Model Evaluation on S2S Time Scales.

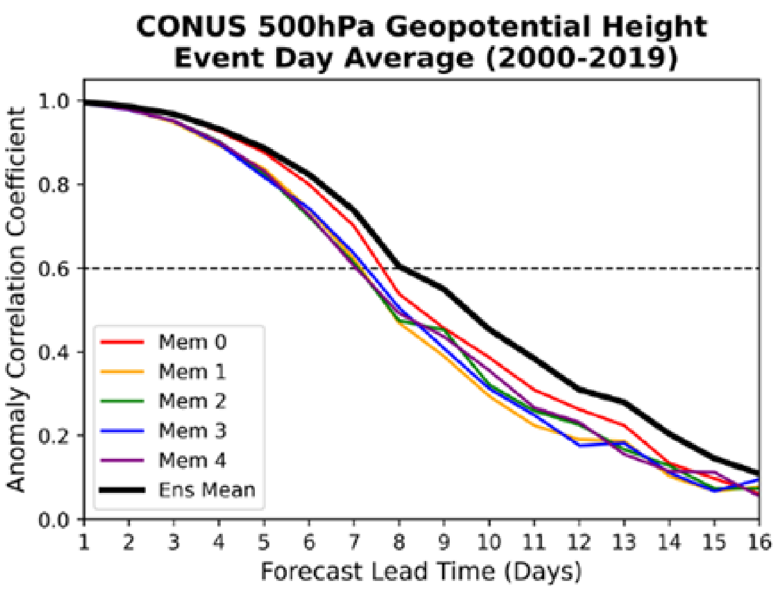


Figure 2-200: Anomaly correlation coefficient (ACC) as a function of lead time, averaged over 181 tornado outbreak events. Colored lines correspond to individual ensemble members, with the black line denoting the ensemble mean. Dashed line marks the skill threshold, ACC=0.6.

CIWRO Themes: Subseasonal-to-Seasonal Prediction for Extreme Weather, Forecast Application Improvements
CIWRO Contributors: Michael Baldwin, Kimberly Hoogewind
Project Title: Evaluation of medium range/S2S severe weather forecasts and analyses
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions and developing reliable probabilistic guidance products.

Developing meaningful, understandable, and useful severe weather forecast products for the medium-range (days 4-15) and S2S (2 weeks - 3+ months) time scales remains a significant scientific challenge. In this project, experimental medium-range probabilistic forecasts of severe weather based upon machine learning algorithms (GEFS-ML) were evaluated. In this case, forecasts were considered successful if they correctly anticipated the maximum category in the corresponding "day 1" SPC convective outlook. In addition, various approaches of quantifying the frequency of severe convective storms within weekly periods in the S2S range were evaluated. The annual cycle of the weekly frequency of days containing severe weather provides insight into when useful forecasts for the second week can be made, as weeks with a higher frequency tend to have the greatest impact. Tangible outcomes from this project include 1 undergraduate student advised, 1 conference presentation, and material included in SPC forecaster training. External partners involved in this project include NCEP/SPC and NOAA/NSSL.

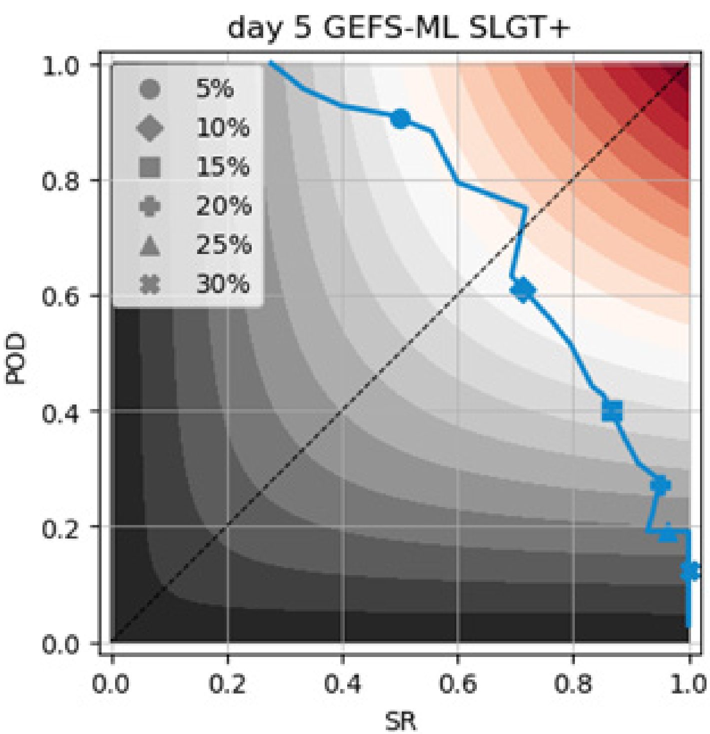


Figure 2-201: Performance diagram indicating how well the GEFS-ML "day 5" domain maximum probability of severe weather (blue) anticipated the occurrence of a "slight risk" or greater in the corresponding SPC 0600 UTC "day 1" categorical outlook during the cool season (mid-Sept through mid-March).

CIWRO Themes: Subseasonal-to-Seasonal Prediction for Extreme Weather Systems, Weather Radar and Observations
CIWRO Contributors: Andrew Osborne, Steven Martinaitis
Project Title: MRMS decadal reanalysis
Relevance to NOAA: This project supports the NOAA mission by creating/improving a trusted analysis of record for model verification/nowcasting.

The MRMS data generated since its initial operational capabilities with the NWS back in September 2014 have gone through various build and scientific updates. This makes the data created during the early operational years of MRMS obsolete compared to the current MRMS product generation. In order to have a continuous dataset that is based on the same science and logic, the MRMS data is being rebuilt from 2014-2023 using the latest MRMS science and logic. The project has developed a comprehensive process to gather and decode various inputs (radar, gauge, model, etc.) and then generate MRMS products for this decadal archive. Each year that is processed is then reviewed for quality assurance and quality control purposes. Developing this ten year MRMS archive based on the latest MRMS science, which will provide data to study seasonal precipitation patterns as well as provide long term precipitation data for hydrologic model calibration for the National Water Model. The current tangible outcomes from this project are a new code set & workflow to create a MRMS archive and two years of complete MRMS data for the archive.

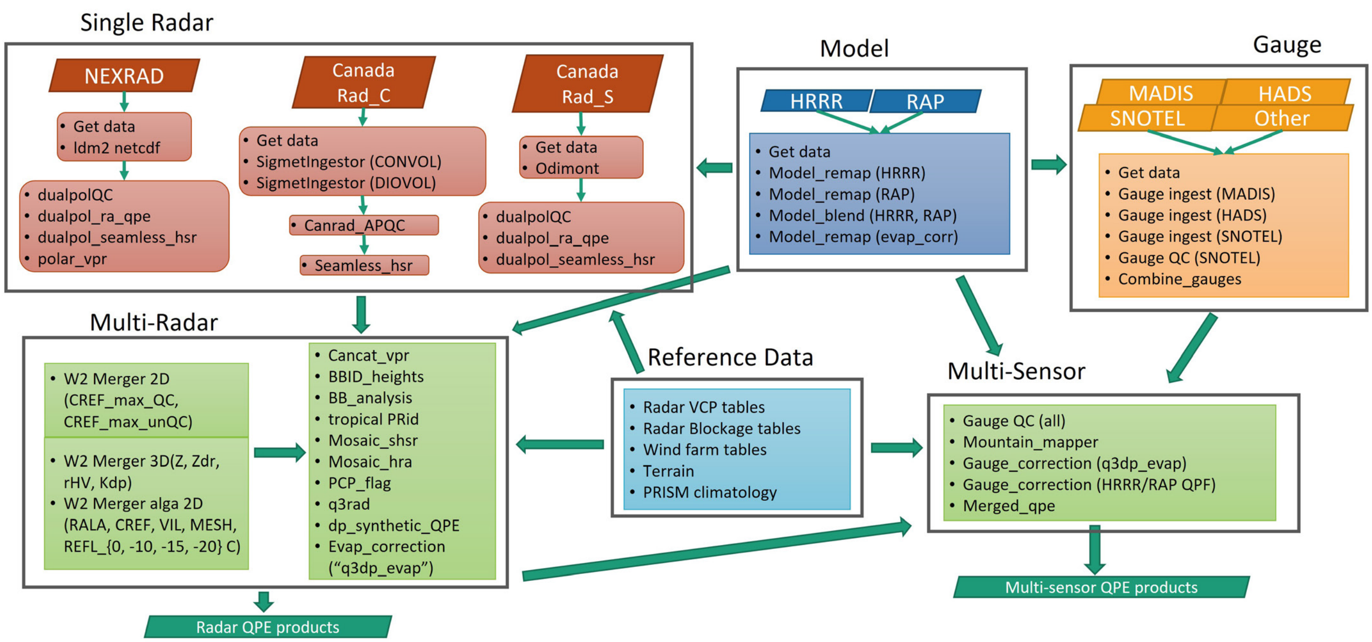


Figure 2-202: Diagram of the workflow to create the MRMS Decadal Reanalysis data.

CIWRO Themes: Subseasonal-to-Seasonal Prediction for Extreme Weather
CIWRO Contributors: J. Scott Greene, W. Ethan Cook, Becca Palczynsky, Alison Holderbaum
Project Title: The assimilation, analysis and dissemination of pacific rain gauge data (PACRAIN)
Relevance to NOAA: This project supports the NOAA mission by creating/improving a trusted analysis of record for model verification/nowcasting, improving observation quality and/or stewardship, improving continuous engagement with partners

The PACRAIN project maintains an online database of in-situ rainfall data over the Tropical Pacific Ocean and gridded rainfall estimates over the same areas derived from atoll and buoy observations. Surface rainfall observations, particularly those made at sea-level and near sea-level locations, which minimize orographic and thermodynamic influences of land masses, provide direct measures of the impacts of changing precipitation distributions, and are indispensable references for validating rainfall estimates based on data from remote sensing platforms (Wimhurst, and Greene, 2021). Through this project, we collected, archived and disseminated PACRAIN rainfall data. We have supplemented island-sited rain gauge records in the database with accumulation estimates derived from rainfall rates observed by buoy-mounted rain gauges and incorporated those records into the online gridded product (Cook and Greene, 2019; 2022). The development of the gridded product within the PACRAIN database provides a better spatial coverage of historical estimates meeting a given threshold of uncertainty and facilitates the inclusion (and validation) of remote sensing data. A key feature of the improved gridded results is the ability to readily estimate rainfall statistics (means, trends, rainfall for a given probability of exceedance, etc.) over specified spatiotemporal domains. The gridded rainfall values and the associated error fields are updated on a monthly basis and made available to stakeholders as are the values in the PACRAIN database itself. In addition to three journal papers, five conference presentations, and two different software releases, PACRAIN archived over 7,000,000 precipitation records. Two graduate research assistants and three undergraduate research assistants were supported by this project.

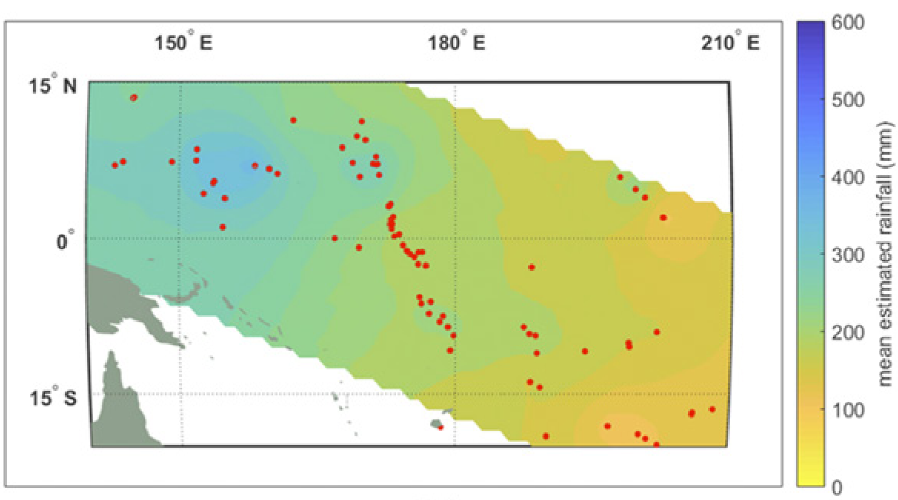
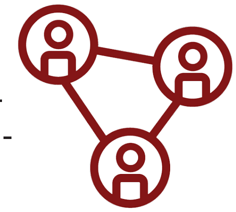


Figure 2-205: Mean estimated rainfall July derived from PACRAIN atoll data (1930-2020)

v. Social and Socioeconomic Impacts of High-Impact Weather Systems



This theme performs social, behavioral, and economic sciences (SBES) research that supports and integrates the other research themes and, ultimately, the NOAA mission to protect lives and property in the face of extreme weather threats. The social and socioeconomic impacts of high-impact weather systems is directly related to the public response to the weather forecast and related hazardous weather information. Ensuring that the public and other stakeholders adhere to weather forecast information is a multi-disciplinary challenge that demands a team science and integrated research approach. Social scientists, meteorologists, emergency managers, and communication and media practitioners need to work closely together to effectively communicate science, weather forecasts, and hazardous weather information, as well as to enhance the messaging of forecast uncertainty to the public.

An important goal set forth in the U.S. Congress' Weather Research and Forecasting Innovation Act is the Tornado Warning Improvement and Extension Program (TWIEP) is "to reduce the loss of life and economic losses from tornadoes through the development and extension of accurate, effective, and timely tornado forecasts, predictions, and warnings, including prediction of tornadoes beyond 1 hour in advance." The TWIEP includes research into ways gap-filling probabilistic information could be generated, disseminated, used by core partners, and ultimately applied to inform decision-making.

These burgeoning research needs require NOAA to institutionalize SBES in various ways, including to attract and retain targeted social scientific expertise. NOAA recognized this need in its Social Science Vision & Strategy (Goal #3). The recent NRC report, "Integrating Social and Behavioral Sciences Within the Weather Enterprise," specifically called out the important role the former CIMMS could play in this arena and, in response, CIWRO core research priorities include societal impacts dimensions, leading us to nurture interdisciplinary and SBES researchers within our workforce and to develop linkages not only with NOAA but also with external researchers and users, forming partnerships that benefit our mission and R2O (research to operations).

Research for this theme within the following foci: (1) evaluating and improving the efficacy of communication of forecasts to partners and the public; (2) improving R2O/O2R linkages for SBES research; (3) improving communication of forecast uncertainty; and (4) cultivating a focus on needs of marginalized populations/communities.

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems
CIWRO Contributors: Holly Obermeier, David Hogg, Taylor Maciag, Justin Sharpe
Project Title: Post-tornado event fieldwork
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, developing reliable probabilistic guidance products, and improving continuous engagement with partners

This project involves CIWRO researchers taking an Integrated Warning Team (IWT) approach to investigating the communication and decision-making environment surrounding select significant tornado events in the United States. CIWRO researchers interview NWS forecasters, broadcast meteorologists, emergency managers and first responders, and members of the public in and near the tracks of select significant tornadoes, generally within 6 to 8 weeks of the tornado event occurring. Interviewees are asked to recount how critical decisions were supported by forecast information or how that forecast information was intentionally communicated across all channels of the integrated warning team to end-users and the public. Thus far, the CIWRO team has deployed this method to study the 10 December 2021 (Mayfield, KY), 4 November 2022 (Idabel, OK), and 24 March 2023 (Rolling Fork, MS) tornado events. This project has resulted in 1 peer-reviewed publication (Trujillo-Falcón et al. 2024), 3 conference presentations, 2 invited talks, and directly changed the way that many NWS Southern Region Forecast Offices communicate severe weather timing uncertainty.

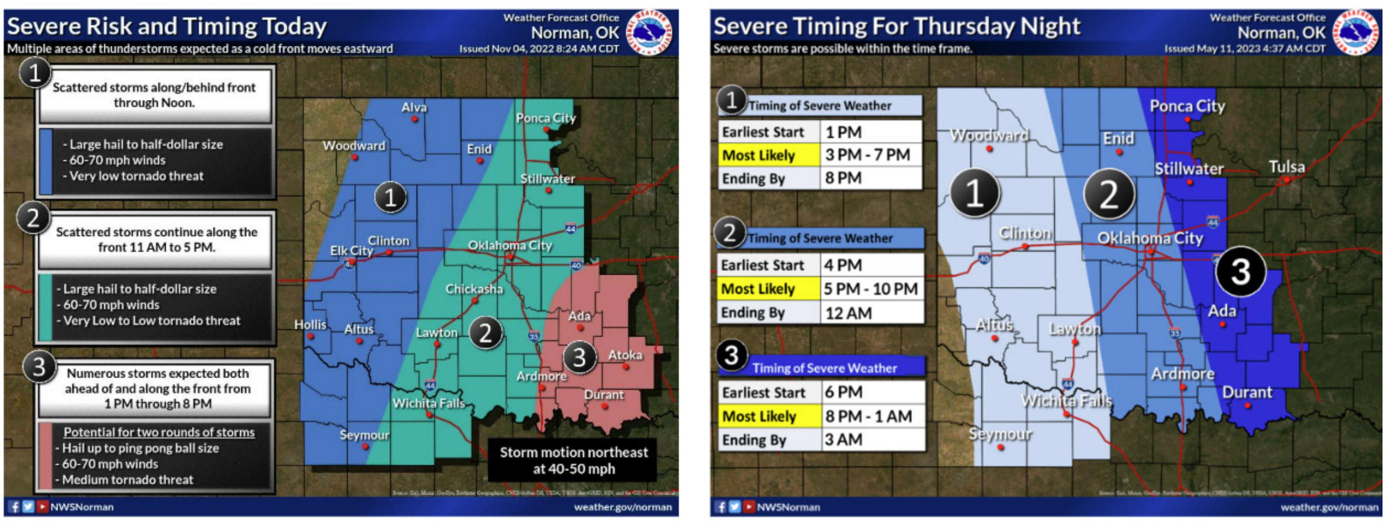


Figure 2-206: Comparison of timing graphics utilized by NWS Norman. The graphic on the right represents the incorporation of uncertainty information, revealed as a critical decision making component through the Post-tornado fieldwork project.

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems
CIWRO Contributors: David Hogg, Miranda Silcott, Holly Obermeier
Project Title: End-user exercises and HWT activities
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, improving continuous engagement with partners, and incorporating social-science principles in new technology/training.

This project includes developing exercises and activities and testing them with NWS forecasters, emergency managers (EMs), broadcast meteorologists, and other end-users. Technologies include Probabilistic Hazard Information (PHI), WoFS, and Watch-to-Warning (W2W) products and were tested in the HWT and at on-site exercises/workshops. The goals of these exercises and activities are to see how these users use and interpret probabilistic forecast information. Most recently, the 2024 W2W experiment was conducted with NWS forecasters and EMs to test how these groups utilize weather information in the space of time after a watch but before a warning is issued. Preliminary results show that EMs utilize several NWS sources during this time period, including NWS Chat, warnings, PHI, local forecast discussions, mesoscale discussions, and various public facing NWS graphics. Tangible outcomes for this project include 6 conference presentations, 1 conference workshop, and 1 peer-reviewed publication (Hogg et al. 2024).

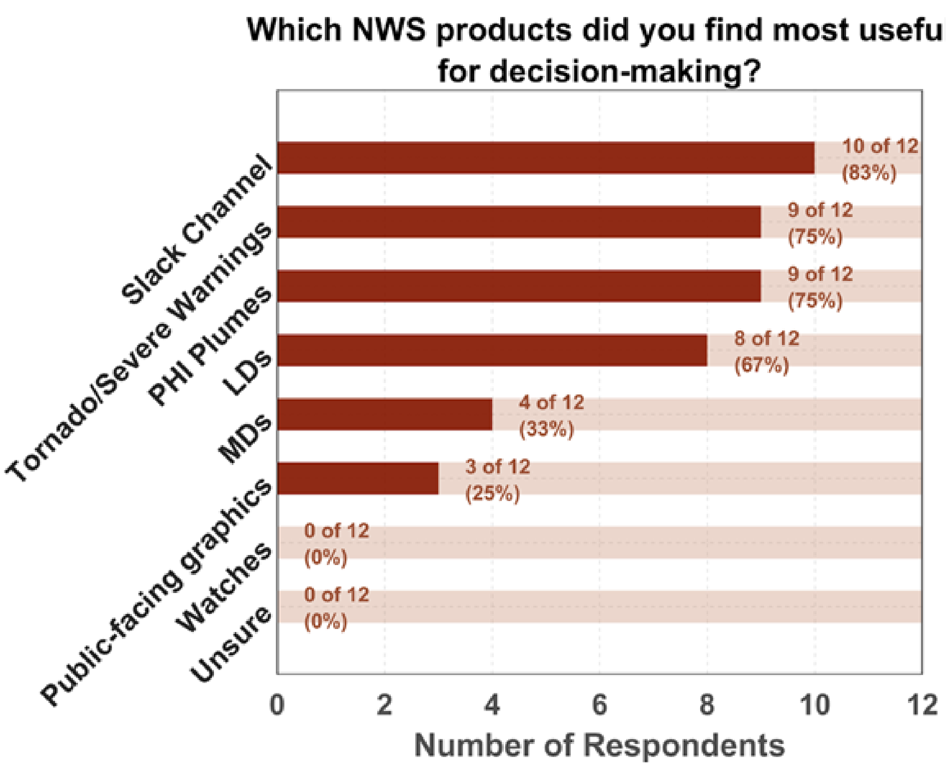


Figure 2-207: EM responses during the W2W experiment of which decision making products they found the most useful. "Slack Channel" refers to NWS Chat, LDs are local discussions, and MDs are mesoscale discussions.

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems, Forecast Applications Improvements
CIWRO Contributors: Eric Loken, Miranda Silcott, Thea Sandmael, Ryan Martz, Adrian Campbell, Rebecca Steeves, Claire Satrio, David Hogg, Patrick Skinner, Katie Wilson
Project Title: Evaluating severe weather watch-to-warning prediction and communication in the HWT
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, developing reliable probabilistic guidance products, and improving continuous engagement with partners.

HWT Watch-to-Warning Experiments (HWT W2WEs) were conducted in 2023 and 2024 (Berry et al. 2024; Lyza et al. 2024). The 2023 and 2024 W2WEs consisted of displaced-real-time case simulations during which SPC and NWS Weather Forecast Office (WFO) forecasters issued new severe weather forecast products. Emergency managers (EMs) used products issued by forecasters to communicate recommendations to decision makers in a parallel EM simulation. Forecasters found SPC-WFO communication particularly valuable for mesoscale analysis-related topics before WFOs began issuing warnings. EMs generally found probabilistic products from forecasters easy to interpret, and many said the products allowed for earlier decision making. Finally, a new machine learning product, called Warn-on-Forecast System - Probabilistic Hazard Information (WoFS-PHI; Loken et al. 2022; Martz et al. 2024), was found to be especially useful for informing local forecast discussions, public graphics, and Mesoscale Discussions. Tangible outcomes include 5 conference presentations and 2 HWT experiments. The project has supported 1 graduate research assistant and 1 hourly undergraduate research assistant for 2 years.

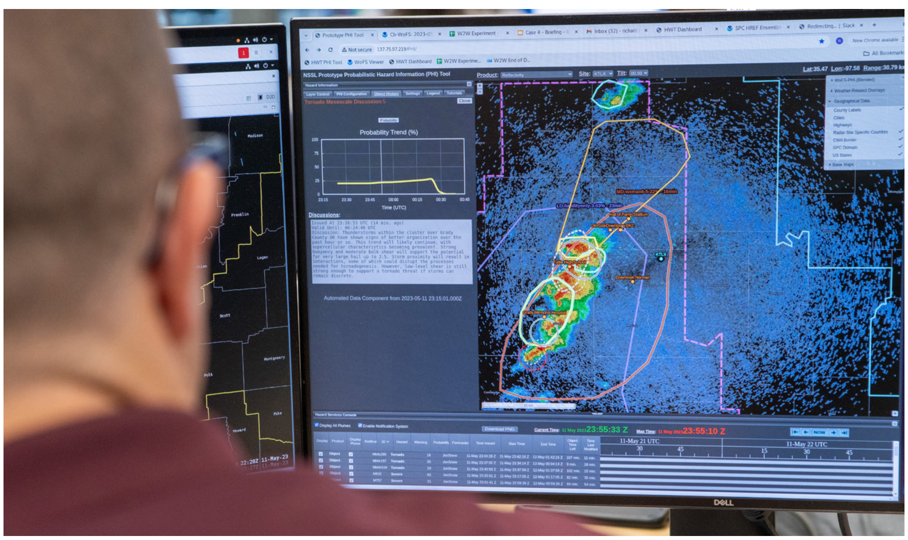


Photo 2-18: A forecaster uses the prototype PHI tool to issue new forecasting products during the 2024 W2WE. Products displayed include an amoeba watch (pink dashed), dynamic warning (gold contour), mesoscale discussion (brown contour), and local discussion (purple contour). Automated ProbSevere (Cintineo at al. 2024; thick yellow contours) and Tornado Probability Algorithm (TORP: Sandmael et al. 2023; thin red, circular contours) objects are displayed as well.

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems
CIWRO Contributors: Holly Obermeier, Taylor Maciag
Project Title: Threats-in-Motion (TIM) testing with end-users
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, improving continuous engagement with partners, and incorporating social-science principles in new technology/training.

This project assesses emergency managers' (EM) and broadcast meteorologists' operational perspectives of Threats-In-Motion (TIM, a rapidly updating warning polygon) and erratic spatial movement through surveys and focus groups. TIM is a major update to operational severe weather and tornado warnings. Testing potential future NWS products during the beginning phases of development can help guide it and ensure that the end product is usable for key partners. In October of 2021, a virtual HWT experiment was conducted with EMs and broadcast meteorologists. During this experiment, researchers showed participants erratic spatial movements of TIM and asked for feedback on how TIM could impact operational workflows. Responses were gathered via surveys and focus group discussions. Results showed that both partners were optimistic about TIM but had some concerns about how it may operate at the local level. For instance, EMs noted that as the warning polygon moved, locations could get "pulled" in and out of a warning multiple times. They worried that the public might find this confusing and inconsistent (Maciag et al. 2025). Furthermore, many of the EMs' operating systems, such as tornado sirens and wireless emergency alerts, would have to be re-configured to handle moving warnings. As TIM continues to undergo developments, further testing will be done with EMs, broadcast meteorologists, and the public. Tangible outcomes for this project include 1 peer-reviewed journal article (Maciag et al. 2025) and 5 conference presentations.

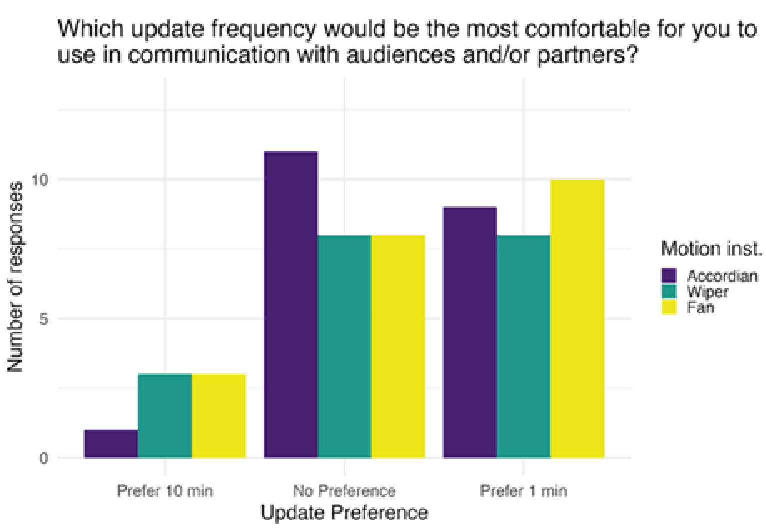


Figure 2-208: Survey responses of EMs indicating which update frequency they were most comfortable with to help them communicate with their audiences or partners. Two update frequencies were applied to the moving TIM warning polygon (1-minute and 10-minute). "Accordion", "Wiper", and "Fan" correspond to three types of erratic spatial movement resulting from the moving polygon.

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems
CIWRO Contributors: David Hogg, Holly Obermeier, Taylor Maciag
Project Title: End-users use of fire weather forecasts and products
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, improving continuous engagement with partners and incorporating social-science principles in new technology/training.

This project involved two components of researching end-user use of fire weather forecasts and products. First, the project surveys emergency managers (EMs) and broadcast meteorologist use of NWS wildfire forecasts and products. Surveys were sent to Oklahoma emergency managers during the spring of 2023 and expanded to Texas emergency managers in 2024. Second, CIWRO researchers conducted interviews with emergency managers, county judges, response personnel, broadcast meteorologists, and NWS forecasters following the Southern Great Plains wildfire outbreak of 26-27 Feb 2024 in Texas and Oklahoma. The goal of these projects is to help understand how end-users use fire weather forecast information from multiple sources, how fire weather forecast and real-time information impacts decision making during events, and to understand how end-users utilize a relatively new and increasingly important NWS product – a 'Fire Warning'. While some data collection is still ongoing, so far a total of 44 EMs were surveyed in Oklahoma, 30 were surveyed in Texas, and over a dozen interviews were conducted in Texas. This project has resulted in 2 conference presentations and 1 reference report. External partners and collaborators on this project include the NWS Forecast Offices in Norman and Amarillo, the State of Oklahoma Forestry Service, Texas A&M Forest Service, Texas Tech University, and the Southern Great Plains Wildfire Outbreak Working Group.

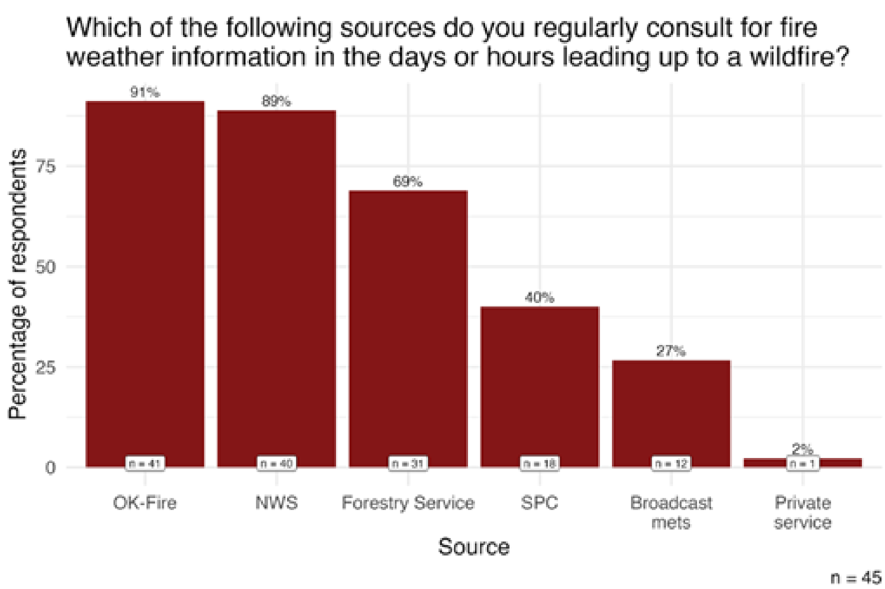


Figure 2-209: Graphic of results asking Oklahoma Emergency Managers to identify the sources of fire weather forecast information that they utilize in the days or hours leading up to a wildfire.

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems
CIWRO Contributors: Justin Sharpe, Taylor Maciag
Project Title: Tornado Tales
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, improving continuous engagement with partners and incorporating social-science principles in new technology/training.

The online citizen science Tornado Tales survey platform allows the public to report their experiences following a tornado to help understand how people obtain, understand, trust, and respond to NWS tornado forecasts and warnings. With sufficient responses, individual responses can be studied at a community level, allowing NWS forecasters to customize messaging for the populations they serve. Version 1.0 was operationalized from 1 February 2023 to 7 May 2024, and Version 2.0 is actively collecting data. Several tornado events have been surveyed to date, for a total of 234 responses. While this is not a sufficient sample size to generalize themes across any area, they do give a first look into how people receive and act upon tornado warning information. For example, 89% of respondents said they received a tornado warning before the event. Tornado warnings were received in a variety of different ways, including via automated texts/phone notifications, tornado sirens, social media, television, the Internet, weather radio, and word of mouth, among others. As the sample size grows, we will learn more. Outcomes to date include 1 reference report, 1 Story Map, 3 conference presentations, 2 national and 4 local television media highlights, 6 web-based news stories, 2 national podcasts, and 1 local news article.

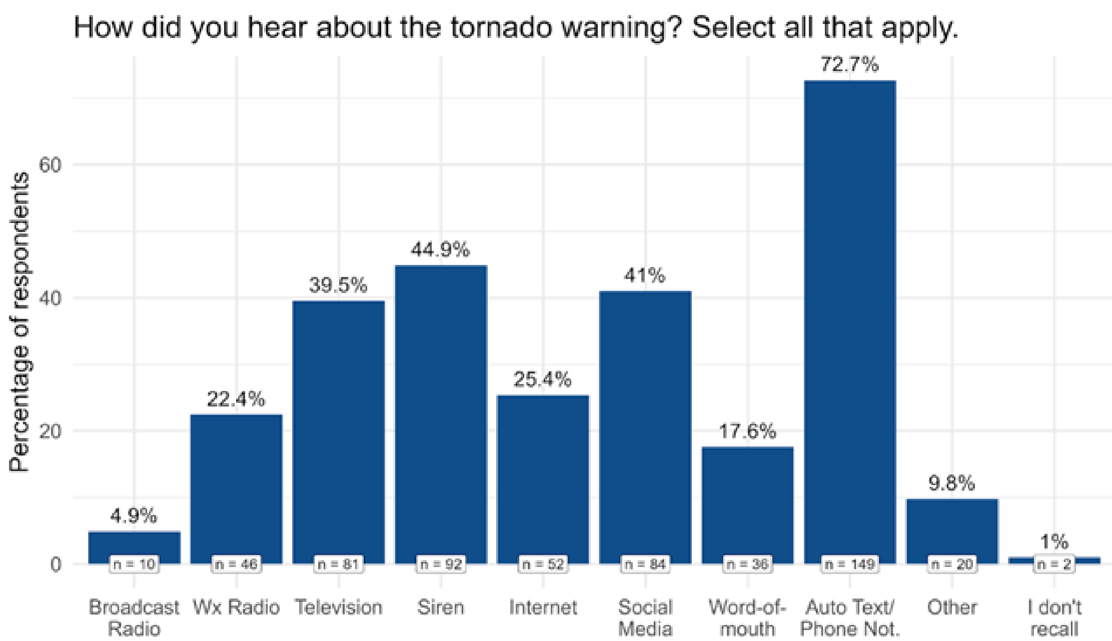


Figure 2-210: Sample survey responses of how respondents recalled receiving a tornado warning.

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems, Forecast Applications Improvements
CIWRO Contributors: Jilliann Dufort, Heather Reeves, Daniel Tripp, Joseph Trujillo-Falcon
Project Title: Human-factors assessments of forecaster interactions with stakeholders, the public, and data for winter storms
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events and improving continuous engagement with partners.

Using traditional social science methods including surveys and focus groups, we are working to characterize how NWS forecasters interact with each other, the public, and decision-support data to understand and message threats due to winter storms. Key findings from this project so far include (1) Most fatalities on roads during winter weather occur in sub-advisory conditions and are characterized by rapidly changing weather (Tobin et al. 2022); (2) NWS forecasters struggle with what probabilistic guidance is appropriate to share with both stakeholders and the public (Tripp et al. 2022); and (3) stakeholders perceptions of the value provided by the NWS for their decision points varies quite widely. Tangible outcomes from this project include 2 peer-reviewed journal articles and 3 conference presentations. External partners involved in this project include the National Centers for Environmental Prediction's Weather Prediction Center, NWS-Amarillo TX, NWS-Cheyenne WY, NWS-Salt Lake City UT, NWS-Wilmington OH, and the University of Illinois at Urbana-Champaign.

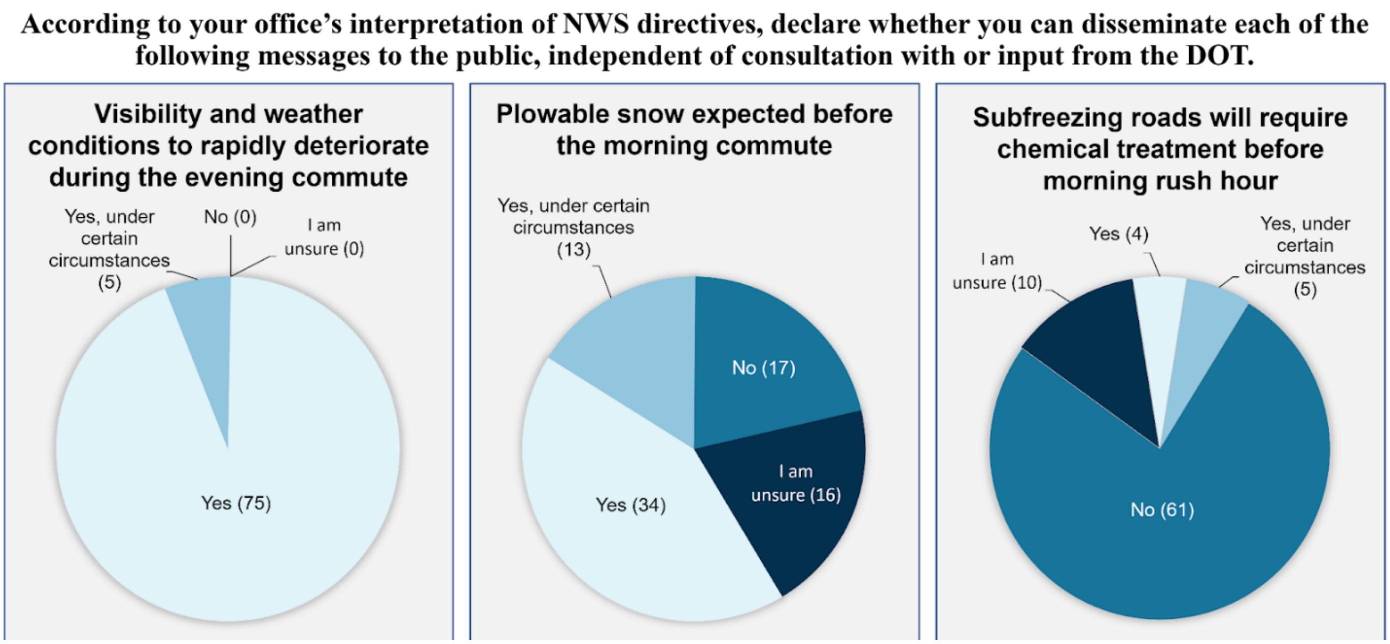
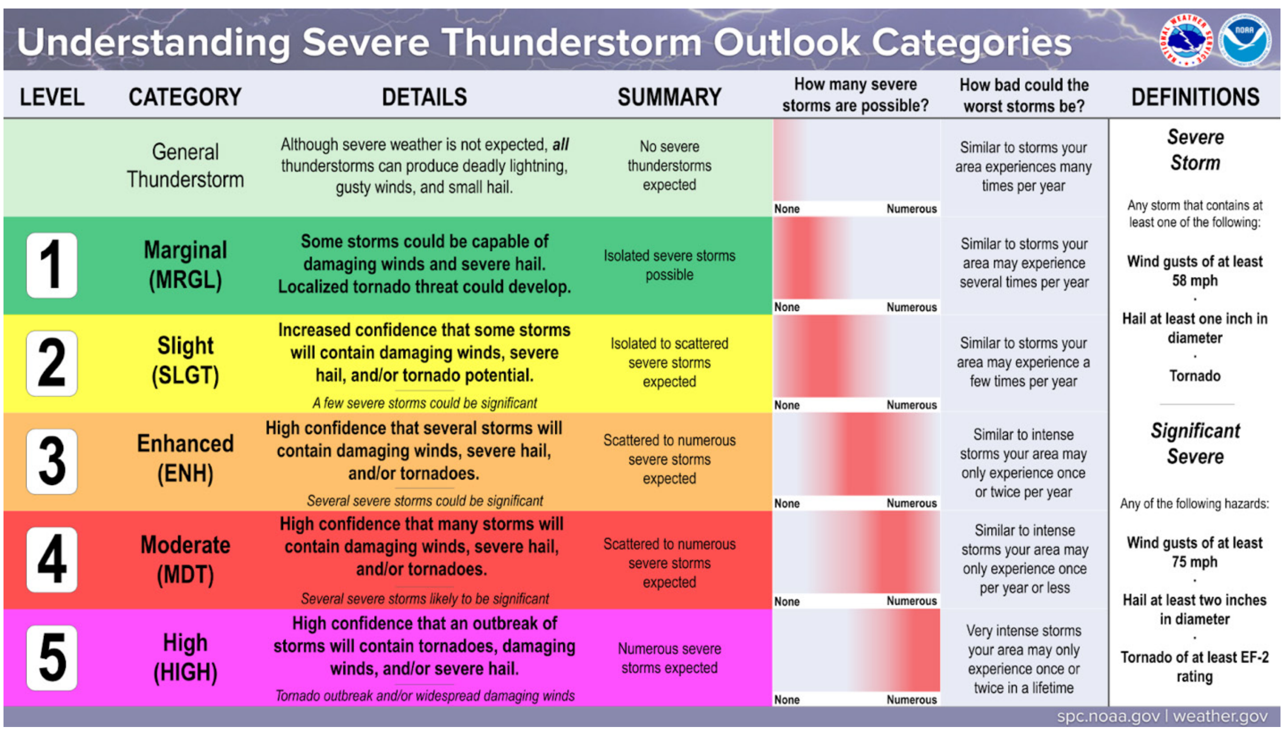


Figure 2-211: Forecasters were asked if they could disseminate each message to the public without first consulting with their respective Department of Transportation. Responses highlight the differing interpretations of NWS directives.

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems
CIWRO Contributor: Joseph Picca
Project Title: Production of new severe weather outlook infographics for public use
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, improving continuous engagement with partners and incorporating social-science principles in new technology/training.

This project involved a collaborative refresh of the SPC's "Understanding Severe Thunderstorm Outlook Categories" public infographic, as well as supporting graphics for Weather Forecast Offices (WFOs), as a working committee of Southern Region Warning Coordination Meteorologists and CIWRO/SPC scientists refreshed the infographics. Informal online surveys of the public were conducted to help them clarify questions they had. For example, individuals were asked to interpret the phrase 'large hail' for guidance on what words to use in the graphic when describing a severe hail threat. There was an open period for feedback from the Southern Region WFOs, and some of their suggestions were incorporated into our updated graphics. The new images provide clearer details and context (relative to the prior outlook graphics) in explaining severe outlook categories to the public, thus enabling improved preparedness to severe weather threats. The primary graphic is available to the public on the SPC homepage, and the additional graphics are distributed by local WFOs. External partners in this project included the NWS Southern Region Headquarters and the SPC.


Understanding Severe Thunderstorm Outlook Categories

LEVEL	CATEGORY	DETAILS	SUMMARY	How many severe storms are possible?	How bad could the worst storms be?
	General Thunderstorm	Although severe weather is not expected, ***all*** thunderstorms can produce deadly lightning, gusty winds, and small hail.	No severe thunderstorms expected	None – Numerous	Similar to storms your area experiences many times per year
1	**Marginal (MRGL)**	**Some storms could be capable of damaging winds and severe hail. Localized tornado threat could develop.**	Isolated severe storms possible	None – Numerous	Similar to storms your area may experience several times per year
2	**Slight (SLGT)**	**Increased confidence that some storms will contain damaging winds, severe hail, and/or tornado potential.** *A few severe storms could be significant*	Isolated to scattered severe storms expected	None – Numerous	Similar to storms your area may experience a few times per year
3	**Enhanced (ENH)**	**High confidence that several storms will contain damaging winds, severe hail, and/or tornadoes.** *Several severe storms could be significant*	Scattered to numerous severe storms expected	None – Numerous	Similar to intense storms your area may only experience once or twice per year
4	**Moderate (MDT)**	**High confidence that many storms will contain damaging winds, severe hail, and/or tornadoes.** *Several severe storms likely to be significant*	Scattered to numerous severe storms expected	None – Numerous	Similar to intense storms your area may only experience once per year or less
5	**High (HIGH)**	**High confidence that an outbreak of storms will contain tornadoes, damaging winds, and/or severe hail.** *Tornado outbreak and/or widespread damaging winds*	Numerous severe storms expected	None – Numerous	Very intense storms your area may only experience once or twice in a lifetime

DEFINITIONS

Severe Storm
Any storm that contains at least one of the following:
Wind gusts of at least 58 mph
Hail at least one inch in diameter
Tornado

Significant Severe
Any of the following hazards:
Wind gusts of at least 75 mph
Hail at least two inches in diameter
Tornado of at least EF-2 rating

spc.noaa.gov | weather.gov

Figure 2-212: The new public-facing severe-weather outlook infographic, which can be found on the SPC homepage (www.spc.noaa.gov).

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems, Forecast Applications Improvements
CIWRO Contributors: Sean Ernst, Benjamin Fellman
Project Title: Investigating user interpretations of conditional intensity forecasts for severe weather
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, improving continuous engagement with partners and incorporating social-science principles in new technology/training.

In this project, we investigated the use of conditional intensity information within severe weather forecasts. To accomplish this, questions from the 2022 and 2023 Severe Weather and Society and 2022 Emergency Manager surveys were analyzed. The first part of this study found that the risk perceptions and mean likelihood of response of both members of the public and emergency managers increased with increasing intensity forecasts, which were denoted by hatched and double hatched regions as seen in Figure 1 (Ernst et al., 2025; forthcoming). These results highlight that intensity information impacts the way individuals perceive their risk to an event and their likelihood of taking protective actions. Following the collection of this first wave of survey data, focus groups were then held with broadcast meteorologists, emergency managers and members of the public to facilitate discussions surrounding conditional intensity information. The discussions in these focus groups provided helpful information regarding language that should be used for intensity information and user preferences of the presentations of this information. Following these discussions, additional questions focused on different presentations of conditional intensity information were asked in the 2023 Severe Weather and Society Survey. This last portion of the study found that additional research will likely need to be performed to understand how this type of information can be best visualized. This project resulted in at least 1 conference presentation and 1 manuscript that is currently in revision. This project was performed in collaboration with the Institute for Public Policy Research and Analysis (IPPRA) at OU and the SPC.

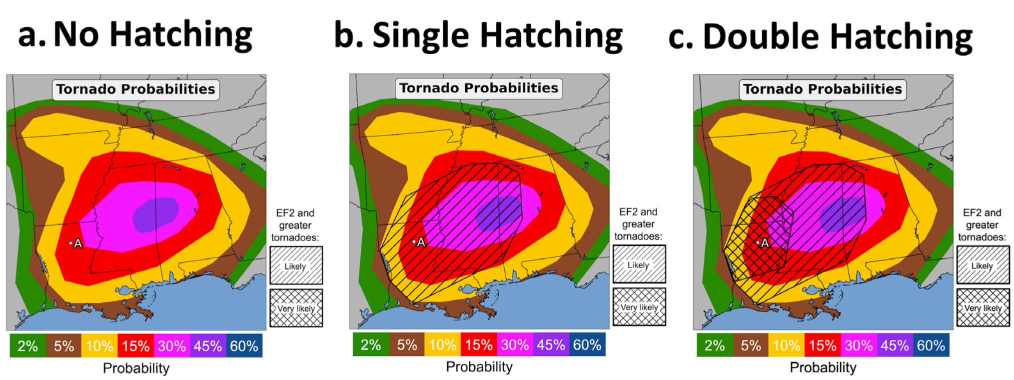


Figure 2-213: Experimental conditional intensity visualizations shown to members of the public and emergency managers in the 2022 Severe Weather and Society (public) and Emergency Manager (EM) surveys. Visualizations increase the conditional intensity forecast hatching level from "none" to "double hatched" across the three versions of the forecast product.

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems, Forecast Applications Improvements
CIWRO Contributor: David Harrison
Project Title: Improving the R2O process through knowledge co-production
Relevance to NOAA: This project supports the NOAA mission by improving continuous engagement with partners and incorporating social-science principles in new technology/ training.

This project solicited feedback from researchers, developers, and operational forecasters to identify how each group assesses the success of a new forecast product and if this assessment differs for products developed using machine learning techniques. Additionally, each group was asked to provide their perspectives on the importance of developer-forecaster collaboration during a product's development cycle. Feedback was collected via a survey presented to participants of the 2021 HWT Spring Forecasting Experiment. The survey asked participants to rate the importance of various factors when deciding whether or not to add a new forecast product to their personal forecasting process. Additional questions asked them to rate the importance of collaboration between researchers and forecasters during various stages of a product's development cycle. The results from this work found that forecasters do not consciously evaluate machine learning products differently than any other new forecast product, but the factors they consider to be most import do differ somewhat from those of researchers and developers (Harrison et al. 2025). The survey results revealed key differences in how researchers and forecasters qualify a product's success, and this was used as justification to recommend increased collaboration between the two groups. Researchers and forecasters both indicated that collaboration was important throughout the development cycle, but less emphasis was placed on the more theoretical and technical aspects of development. We applied this feedback during development of our proposed R2O model to better specify the type and amount of collaboration recommended at each step of the process (Harrison et al., in review). Tangible outcomes from this project include 2 journal articles, 2 conference presentations, 1 masterclass, and 4 invited talks. This project was performed in collaboration with the SPC, the National Science Foundation's Artificial Intelligence for Environmental Sciences (AI2ES), the National Center for Atmospheric Research (NCAR), and the University of Washington.

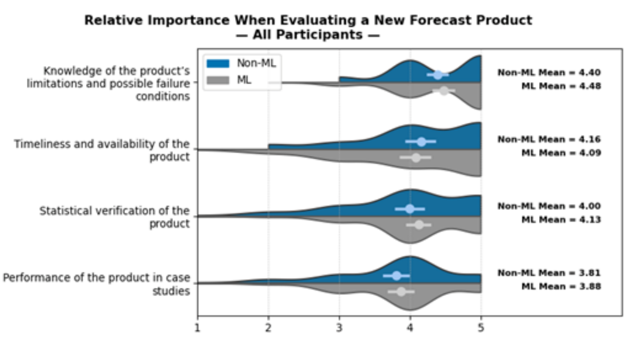


Figure 2-214: Response distributions for the top four factors that researchers and forecasters consider when evaluating the success of a new machine learning and non-machine learning forecast product.

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems, Forecast Applications Improvements
CIWRO Contributors: Michael Baldwin, David Harrison, Sean Ernst
Project Title: Perceptions and performance of global AI NWP models
Relevance to NOAA: This project supports the NOAA mission by improving weather and water predictions, incorporating social-science principles in new technology/training, and maturing the next-generation earth system models.

Artificial intelligence (AI) methods for emulating global Numerical Weather Prediction (NWP) models have been advancing at an extremely rapid pace in recent years. While several studies have evaluated these AI/NWP models using traditional statistical measures, user-focused evaluations within an operational forecasting environment have yet to be attempted. In the 2024 NOAA HWT, we measured user perception and objective performance of several global AI/NWP models along with the NOAA Global Forecast System (GFS). Objective accuracy measures showed the AI models had similar levels of performance as the GFS, while subjective ratings indicated that the GFS was the preferred system in the majority of cases. This project highlights several challenges for forecast evaluation, since results from statistical verification often disagree with human/subjective impressions of forecast performance. Tangible outcomes from this project include 1 conference presentation. External partners involved in this project include the SPC, the National Science Foundation's AI2ES, and the Institute for Public Policy Research and Analysis (IIPRA) at OU.

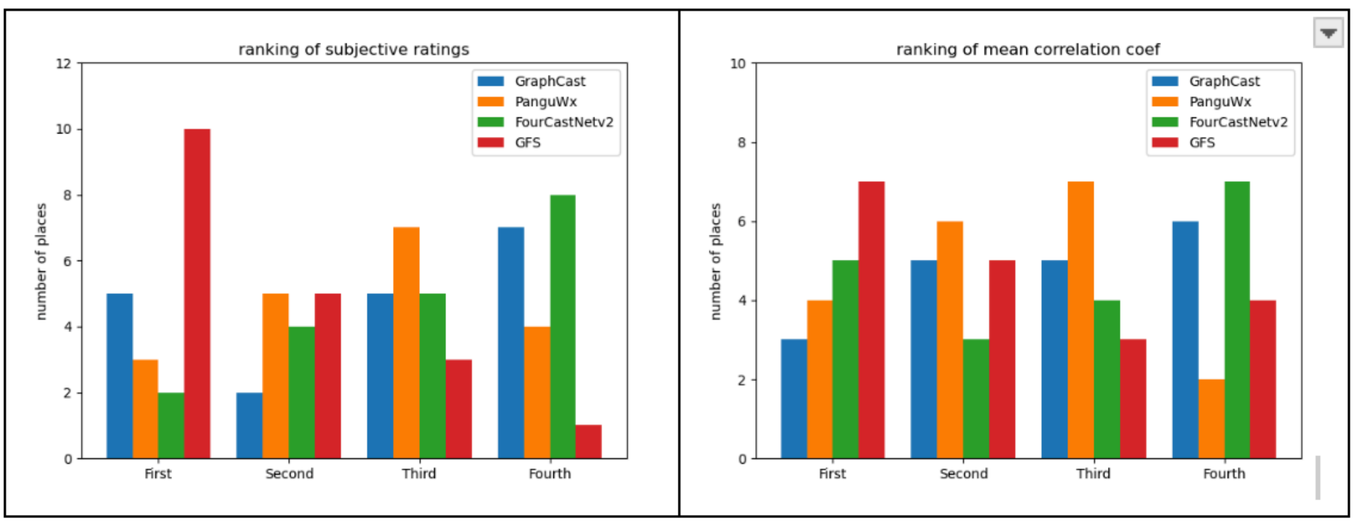


Figure 2-215: Comparison of daily rankings of subjective (left) and objective (right) evaluations comparing three AI/NWP systems (GraphCast, PanguWeather, FourCastNetv2) and one physics-based NWP system (GFS) during the 2024 NOAA HWT Spring Forecast Experiment, lead times 156-180h ("day 7").

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems
CIWRO Contributor: Justin Sharpe
Project Title: VORTEX-Southeast/Mississippi-Alabama sea grant outreach & engagement
Relevance to NOAA: The project provides opportunities for two-way dialog that contributes to the understanding of on-the-ground needs of audiences vulnerable to severe weather events. NOAA can directly respond to those needs with accurate, trusted information delivered by extension specialists, researchers, and other experts.

This project is a partnership between NSSL and Mississippi-Alabama Sea Grant to translate research from VORTEX–Southeast into practical on-the-ground knowledge and actions. The project supports participatory action research through collective inquiry and experimentation grounded in experience and social history. It has included 50 training events that have provided in-person training for 2,300 people plus outreach products that have reached more than 5,000 people online. This project involves 26 partner organizations.

Photo 2-19: Outreach event in Selma, Alabama

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems
CIWRO Contributor: David Jahn
Project Title: Markov Chain Monte Carlo model to predict wildfire suppression costs
Relevance to NOAA: This project supports the NOAA mission by developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events, and developing reliable probabilistic guidance products.

A Markov Chain Monte Carlo (MCMC) model provides a probabilistic forecast of project cost related to wildfire suppression in consideration of SPC (SPC0 fire outlook areas and risk levels. The model is constructed using 6-year distributions of the number of wildfires per unit area and burn area per wildfire, each for which a Weibull curve is fit. Wildfire information is available from an open-source database (St. Denis et al. 2023). Based on 10,000 random simulations, probability density functions (PDFs) are generated that provide a probabilistic forecast of total burn area for an SPC outlook of a given areal extent. A bivariate spline surface is fit to a two-dimensional histogram of observed values of burned area and associated project cost to formulate a statistically viable project cost for each of the 10,000 simulations, resulting in a PDF of forecast project cost for wildfires of a specific SPC outlook for a specific day. This probabilistic forecast of fire suppression costs is potentially useful for fire managers in the optimal allocation of resources for the fighting of wildfires. This work has to date produced 1 conference presentation.

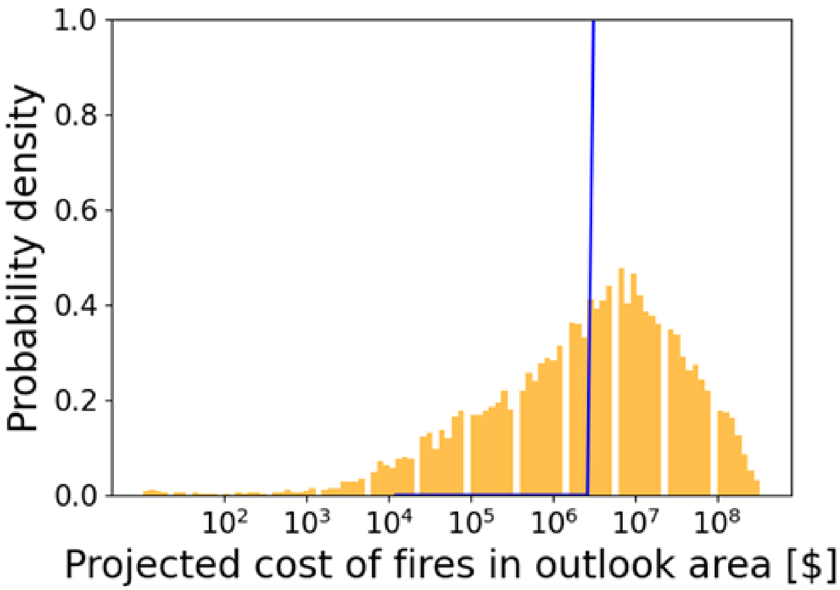


Figure 2-216: Simulated probability distribution (gold) of projected fire suppression cost for fires within a SPC fire outlook of 2020-08-06 as compared to actual cost (vertical blue line).

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems
CIWRO Contributors: Joe Ripberger, Sean Ernst, Anna Wanless, Zoey Rosen, Abby Bitterman, Hank Jenkins-Smith, Carol Silva
Project Title: Analysis of longitudinal extreme weather and society data and development of the flood weather survey and dashboard
Relevance to NOAA: This project supported NOAA's mission by incorporating social-science principles in new technology/training, developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events and incorporating social-science principles in new technology/training, and improving continuous engagement with partners.

IPPRA conducts an annual survey to assess public reception, understanding, and response to forecasts and warnings for multiple hazards, including severe convective weather, tropical weather, winter weather, and flooding. These data support analyses of how NWS policies and programs evolve over time and across regions, offering forecasters and partners critical insights into the communities they serve. This project facilitated longitudinal analyses of survey data and contributed to the development of the annual flood survey. It also supported the development and analysis of multiple survey experiments that inform NWS risk communication strategies. Tangible outcomes from this project included 4 formal journal articles and 12 conference presentations. External partners included the NSF National Center for Atmospheric Research and the Nurture Nature Center.

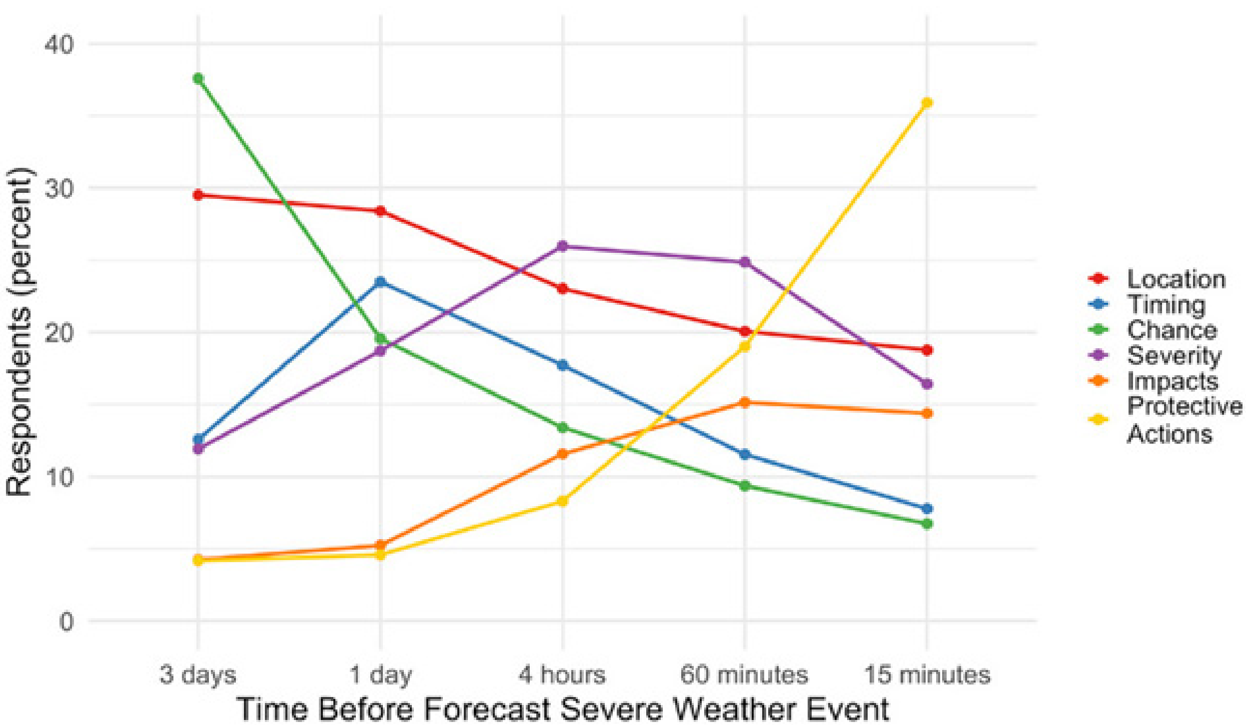


Figure 2-217: Figure from a study that measured public information priorities across weather hazards and time scales.

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems
CIWRO Contributors: Holly Obermeier, Jeannette Sutton, Kodi Berry, Michael Michaud, Heather Sheridan, Gregory Cox, Caroline Rafizadeh, Savannah Olivas, Nate Johnson, Makenzie Krocak, Joseph Trujillo-Falcón, Ling Ling Sun
Project Title: Viewer preferences for next-generation media content during severe weather
Relevance to NOAA: This project supports the NOAA mission by improving continuous engagement with partners and incorporating social-science principles in new technology/training

In this project, the research team investigated viewer preferences for graphics, text, and level of interactivity with severe weather data received through NextGen TV. We conducted content analyses, eye-tracking interviews, and focus groups to explore how extreme weather information is presented on television broadcasts, what information viewers want to access, and what information they pay most attention to. We found that screens use consistent designs but vary in their presentation, likely due to branding (Michaud et al. 2024). Screen design affects visual attention, where busy graphics and mismatched background imagery to text can be distracting to viewers (Rafizadeh et al. Under Review). There has been a lack of social science research to support the design of screens, for which we further advocate in future studies (Michaud et al. Under Review). This research has resulted in 2 conference presentations at AMS, and 3 journal papers (2 are currently in review). At the University at Albany, 2 graduate students participated in this research (not funded through the award). At CIWRO at OU, one researcher led five (5) focus groups with members of the public to assess visualizations of what severe weather information could look like in a NextGen TV environment. This research was done in conjunction with Nebraska Public Media. External collaborators are included in the list of contributors above, and include Nate Johnson from NBC Universal and Ling Ling Sun from PBS.

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems
CIWRO Contributors: Joe Ripberger, Sean Ernst, Anna Wanless, Zoey Rosen, Abby Bitterman
Project Title: Continuing research and collaboration on the severe weather survey and dashboard (Y1, Y3, and Y3)
Relevance to NOAA: This multi-year, ongoing project supports NOAA's mission by incorporating social-science principles in new technology/training, developing improved methodologies to produce and/or communicate warning uncertainty for high-impact weather events and incorporating social-science principles in new technology/training, and improving continuous engagement with partners.

IPPRA conducts an annual survey to assess public reception, understanding, and response to forecasts and warnings across multiple hazards, including severe convective weather, tropical weather, winter weather, and flooding. These data support analyses of how NWS policies and programs evolve over time and across regions, providing forecasters and partners with critical insights into the communities they serve. This multi-year project enables ongoing data collection and dissemination through "WxDash", an interactive platform that offers dynamic access to survey data for research, policy evaluation, and risk communication improvements. Tangible outcomes from this project included 2 formal journal articles and 4 conference presentations. External partners included the NWS Social, Behavioral, and Economic Sciences (SBES) Program.

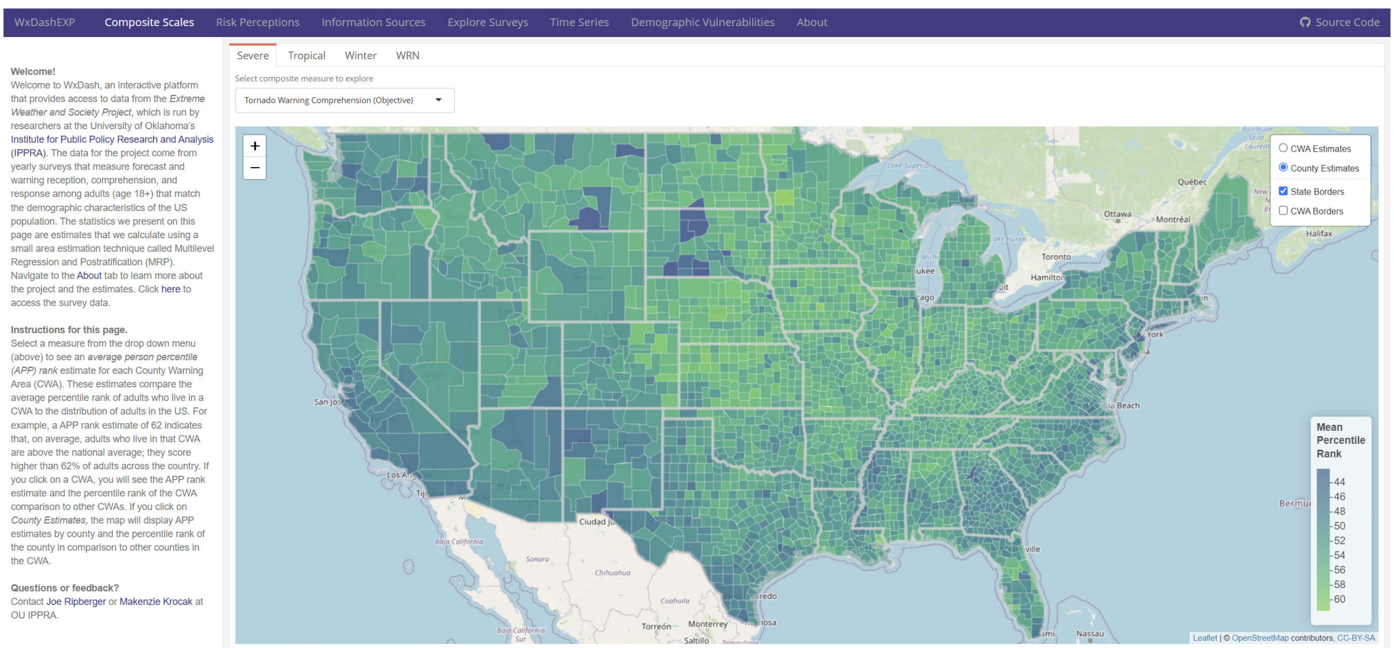


Figure 2-218: Screenshot from WxDash, the interactive platform that offers dynamic access to survey data for research, policy evaluation, and risk communication improvements.

CIWRO Theme: Social and Socioeconomic Impacts of High-Impact Weather Systems
CIWRO Contributors: Joe Ripberger, Anna Wanless, Maggie Leon-Corwin
Project Title: Statistically exploring the relationship between social vulnerability and tornado warning reception, comprehension, and response
Relevance to NOAA: This project supported NOAA's mission by incorporating social-science principles in new technology/training and incorporating social-science principles in new technology/training and improving continuous engagement with partners.

This study examined how geographic indicators of social vulnerability influence public reception, comprehension, and response to tornado warnings. Results showed a modest link between census-based social vulnerability and survey-based measures of tornado warning reception, understanding, and response. On average, respondents in socially vulnerable areas were less likely to receive, understand, or respond to warnings. These results were used to help the NWS refine risk communication approaches in vulnerable areas of the country. Tangible outcomes from this project included a conference presentation and a briefing to NWS leadership. External partners included the NWS Social, Behavioral, and Economic Sciences (SBES) Program.

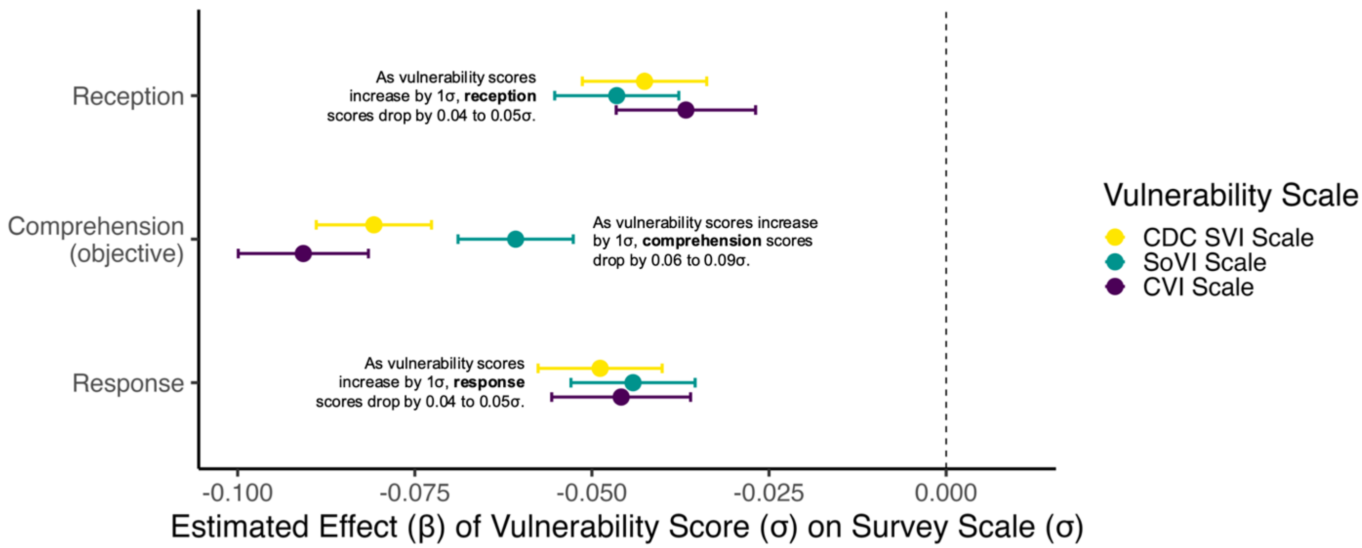


Figure 2-219: Figure from a study on the relationship between social vulnerability and tornado warning reception, comprehension, and response.

b. Social Sciences/Human Dimensions

The fifth theme of CIWRO research is social and socioeconomic impacts of high-impact weather systems, with contributions from this theme described above. Because the mission of CIWRO is to enhance understanding of weather phenomena that meets NOAA's goal of improving watches and warnings that save lives and property and minimize the economic damage of high-impact weather, this fifth theme integrates the understanding and products gained from the other 4 thematic areas, and addresses the social sciences and human dimensions as elaborated upon in the discussion below.

i. How are social science questions or topics included in CI funded research?

Social science questions and topics are included in CIWRO funded research either as funded projects in that specific theme or as components of other funded projects that also make contributions to CIWRO's other four themes. For example, social science topics are included in activities of the Hazardous Weather Testbed (which is included in the "forecast application improvements" theme) in projects such as "End-User Exercises and HWT Activities" and "Evaluating Severe Weather Watch-to-Warning Prediction and Communication in the HWT." Further, in coordination with the Threats in Motion (TIM) forecast improvement work, there are projects assessing emergency manager and broadcast meteorologists' operational perspectives, and also end-users use of and evaluation of fire weather forecasts and products. Thus, it is seen that the social sciences and topics included in CIWRO's research portfolio are highly integrated with work from the other themes.

ii. Is there an explicit social science agenda in ongoing research?

There is an explicit social science agenda as it is the fifth CIWRO theme. Furthermore, social science research at CIWRO is heavily integrated with work from other themes, particularly as relates to work in forecast application improvements.

iii. How much social science does the CI currently fund?

Since the formation of CIWRO, $2,380,581 of funding has been received for social science projects covered under the fifth theme. Of $70,278,596 total funding to CIWRO in that time period, social science represents 3.4% of CIWRO's funded portfolio. The social science funded projects and accomplishments are described in Section 2.a.v. above.

iv. What are the major roadblocks to expanding social science in the research plan or portfolio?

The major roadblocks to expanding social science in the research plan revolve around a lack of resources needed to pursue social impacts research, with the three key missing resources being people, data and funding. Societal impacts research in meteorology needs more social

scientists and *social-science-trained meteorologists* to answer a broad and growing list of important research questions. There is also a lack of physical and social data collected on the societal impacts of weather, and the impact data that is collected (such as wintertime road conditions) is rarely standardized, cleaned, or easily available to researchers. Finally, limited funding exists for incorporating societal impacts research into typical physical meteorology studies, and there is a lack of positions for social scientists with more stable funding (such as Task II funding).

Potential sources of these hindrances can again be organized around people, data, and funding. The limited number of social scientists studying the societal impacts of weather can be attributed to a lack of awareness of or interest in the topic or to scarcity of funding sources to support such work, in addition to the inflexibility of current meteorological education standards that prevent students from pursuing a more specialized, multidisciplinary education. Funding for societal impacts research in meteorology is more limited by the lack of added funding in calls for proposals for social science study, in addition to the lack of societal-impacts research-scientist positions with stable funding. Finally, data collection on societal impacts suffers from the lack of people and funding needed to do the hard work of data collection and cleaning, including consistent long-term funding for longitudinal and rapid-response survey deployment and the development of data visualization and access tools (such as those presented by the IEM or OU IPPRA, see https://mesonet.agron.iastate.edu/ and https://crcm.shinyapps.io/WxDashExp/). A lack of national standards for the collection of societal impact data has also stymied any improvements in social impact data storage. Of note is the fact that all of these hindrances are exacerbated by the lack of understanding of social science study design, theory, and application that physical scientists have, due to their lack of exposure to social scientists or social science research methods.

v. What is the CI's plan for addressing social science issues?

There are ways that new observations and efforts can address the major resource gaps. First, the collection of societal impacts data needs to be modernized using cutting edge tools, such as drone surveys for physical impacts, and cell phone apps for social impact data. These data also need to be made more accessible, through the creation of dedicated and user-tested data viewers, collaboration with Institutional Review Board (IRB) and Office of Management and Budget (OMB) to set standards for safe and respectful data access, and by making datasets available in standardized formats from easily found repositories. Funding for societal impacts research also needs to account for the significant differences in running costs that social science measurements require compared to physical science measurements, which have higher upfront but lower maintenance costs compared to survey efforts. Finally, bureaucratic changes must be made such that social scientists working with meteorologists are not tokenized and separated from their peers, which would have the additional bonus of taking social science research responsibilities away from physical scientists such that both experts can focus their time on work requiring their specific expertise.

For CIWRO to address these social science issues the most important component is acquisition and availability of more funding. Other planned efforts are summarized as follows:

- Efforts to make social science data more accessible to other researchers should be encouraged and would be highly valued.
- CIWRO scientists are expected to co-develop new research with social science partners from the start of the research process.
- CIWRO makes efforts towards “bridge-building” where scientists and social science partners are brought together through outreach and workshop organization. This is done through many of the workshops that CIWRO has organized, but more efforts can be made in this realm.
- CIWRO seeks to leverage opportunities for citizen science whenever possible, to both improve data collection on societal impacts but also to incorporate new and unexpected perspectives on research findings and products.
- CIWRO plans to work with its academic contacts, including its university and academic partners and the American Meteorological Society, to encourage meteorology students interested in interdisciplinary studies to gain expertise in multiple knowledge areas, including the social sciences and the study of societal impacts of weather. This may include the development of new curriculum requirements and new classes that cover interdisciplinary topics.
- The School of Meteorology at OU is currently hiring a new tenure-track professor in the theme of Societal Impacts, with the planned starting date August 2025. CIWRO plans to heavily integrate the new faculty member into its activities and have frequent collaborations with CIWRO employees in project execution and proposal development.
- Ideally with new funding, CIWRO plans to work with collaborators and informed end-users to establish clear research objectives that help CIWRO prioritize funding across multiple key societal impacts study needs, including:
    - Developing new societal impacts data viewers and repositories;
    - Hiring subject-matter experts that can lead co-development with and training of partners including Emergency Managers;
    - Developing materials for training users including operational meteorologists on proper use of the products of CIWRO research, either in-house or through collaboration with CIWRO partners like the WDTD.

3. EDUCATION AND OUTREACH

a. What types of educational activities/opportunities does the Institute offer on an ongoing basis?

Through Task I funding, through professional development activities for CIWRO staff members, and through volunteer activities of CIWRO staff, CIWRO offers many educational activities and opportunities on an ongoing basis. These activities are described below according to the target audience.

K-12 Education

CIWRO offers a variety of educational activities/opportunities for K-12 education. These activities are coordinated by the OU outreach coordinator and include the following:

- **Classroom visits:** CIWRO employees make regular visits to K-12 classrooms across the state of Oklahoma. We try to reach schools throughout the entire state, including those that border other states and that involve substantial drive time from Norman. A non-comprehensive list of schools visited since CIWRO was created in October 2021 include Canyon Ridge Intermediate School, Anadarko Middle School, Maryetta Junior High, Ada Junior High, Norman High School, Southridge Junior High School, Piedmont Middle School, Deer Creek Elementary School, Hulbert Elementary School, Cushing Elementary School, McLoud Elementary School, Cache Middle and Elementary School, Meeker Elementary School, and Canton Middle School. The content presented at the schools varies depending on the request of the teachers and the grade level of the students, but generally involves active learning demonstrations of weather phenomena, playing weather games, answering student questions about weather phenomena or career paths, and allowing students to get to know scientists and their career path so that they can visualize themselves as scientists. Although we visit any school that requests visits, as per researchers' availability, we specifically target schools well outside of Norman and Oklahoma City where visits from scientists are less common than for schools in the Oklahoma City metropolitan area. On a recent visit to Anadarko Middle School, the science teacher remarked we were the first scientists to visit her classroom in her 19-year teaching career. Thus, we are hoping that our efforts are helping to overcome the unequitable access to resources that some of these school districts in the remote areas of Oklahoma currently have. Classroom visits have also included participation in career fairs at various schools throughout Oklahoma.
- **Creation and loaning of travelling trunks**: CIWRO has created traveling trunks which are loaned out free of charge to elementary classroom teachers in the state of Oklahoma. Teachers call them "Weather in a Box." These are pre-assembled kits complete with comprehensive lesson plans and supplies for hands-on learning and are part of our outreach to provide opportunities to educate, empower and inspire students to learn more about the weather around them and consider career pathways in meteorology and related fields. The included lessons also tie science into other disciplines like reading and math.

Each trunk highlights different weather phenomena, and thus far four trunks have been developed: cloud trunks for grades PK-2 and grades 3-6, and tornado trunks for grades PK-2 and grades 3-6. Details about the travelling trunks are available at https://www.ou.edu/ciwro/educate/pk-12, where one can find the lesson plans and supply list included in the trunk. Thus far, 12 different teachers in Cleveland and Love Counties in Oklahoma have checked out the trunks.

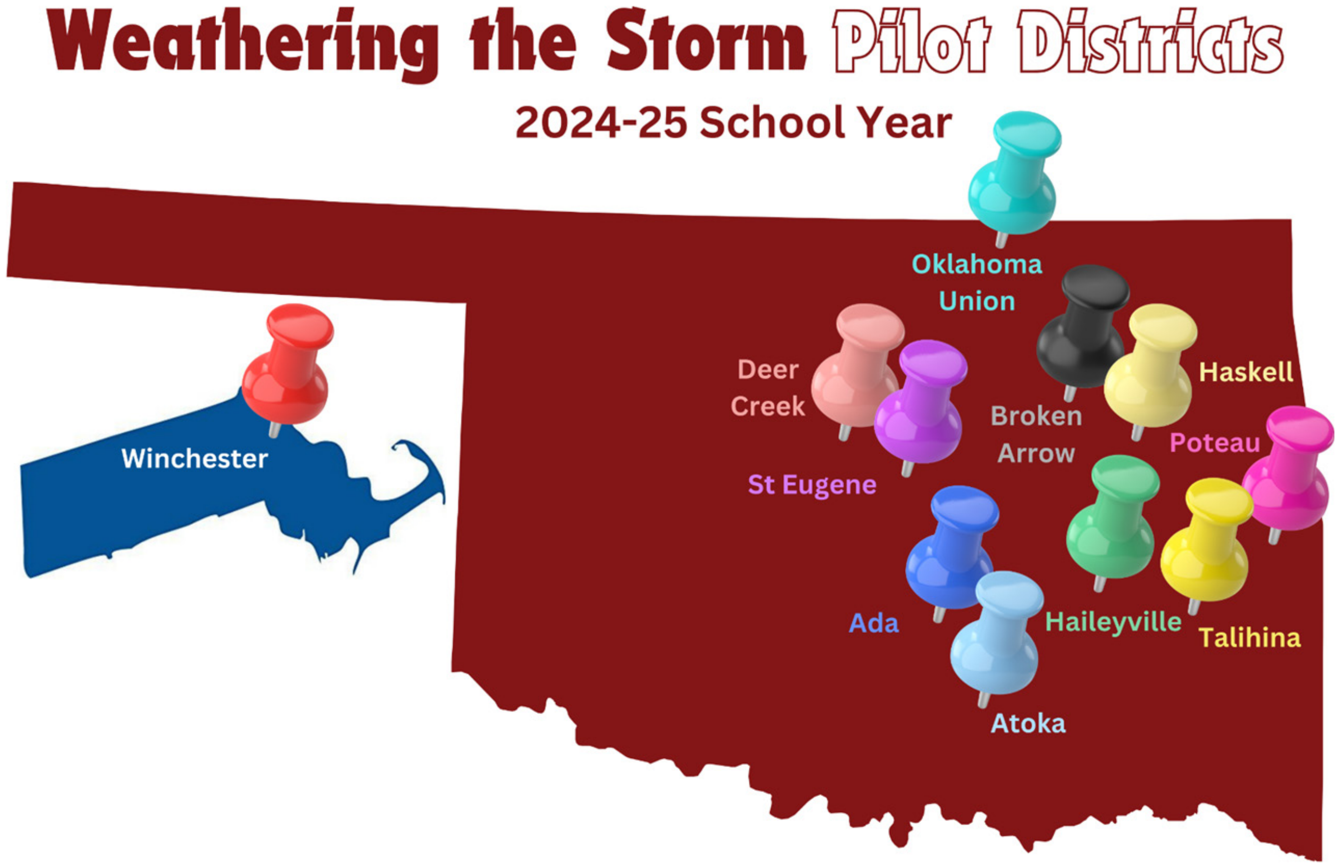


Figure 3-1: Districts piloting the CIWRO middle school curriculum in the 2024-2025 academic year.

- **Development of curriculum**: Working with the Tulsa Regional STEM Alliance, CIWRO has developed a meteorology curriculum for middle school students that is now being piloted at 10 different schools in Oklahoma and 1 in Massachusetts as illustrated in Figure 3-1. The Tulsa Regional STEM Alliance is a nonprofit organization that cultivates impactful partnerships and learning pathways that inspire and prepare all youth for a STEM-enabled future and is dedicated to providing educators with access to high-quality instructional materials. We have collaborated with the Tulsa Regional STEM Alliance to develop and support the implementation of a 9 to 18-week middle school career exploratory elective meteorology course called "Weathering the Storm" that aims to inspire and prepare students in the field of meteorology. The materials are designed using the EEL DR C model developed by Deporter et al. (1999), which is a constructivist approach to teaching that helps students find connections with new information while accommodating various learning modalities and multiple intelligences. Students are placed at the center of learn-

ing so that the lesson plans support students' background knowledge and the individual ways they make sense of the world. The Oklahoma Academic Standards for Science, Math and Computer Science were incorporated into the curriculum where appropriate, but the materials were not intended to be inclusive of all middle school science standards. The course consists of the following units: 1) the atmosphere; 2) wind; 3) clouds and precipitation; 4) storms; 5) tornadoes and hurricanes; and 6) forecasting and severe weather research. Each unit has the following parts: 1) STEM-focused content, 2) observations in the sky, 3) equity/citizen science/safety; and 4) meet a professional spotlight. The material in this course can also be used as supplementary material for science classes and it is also suitable for after-school clubs and summer camps.

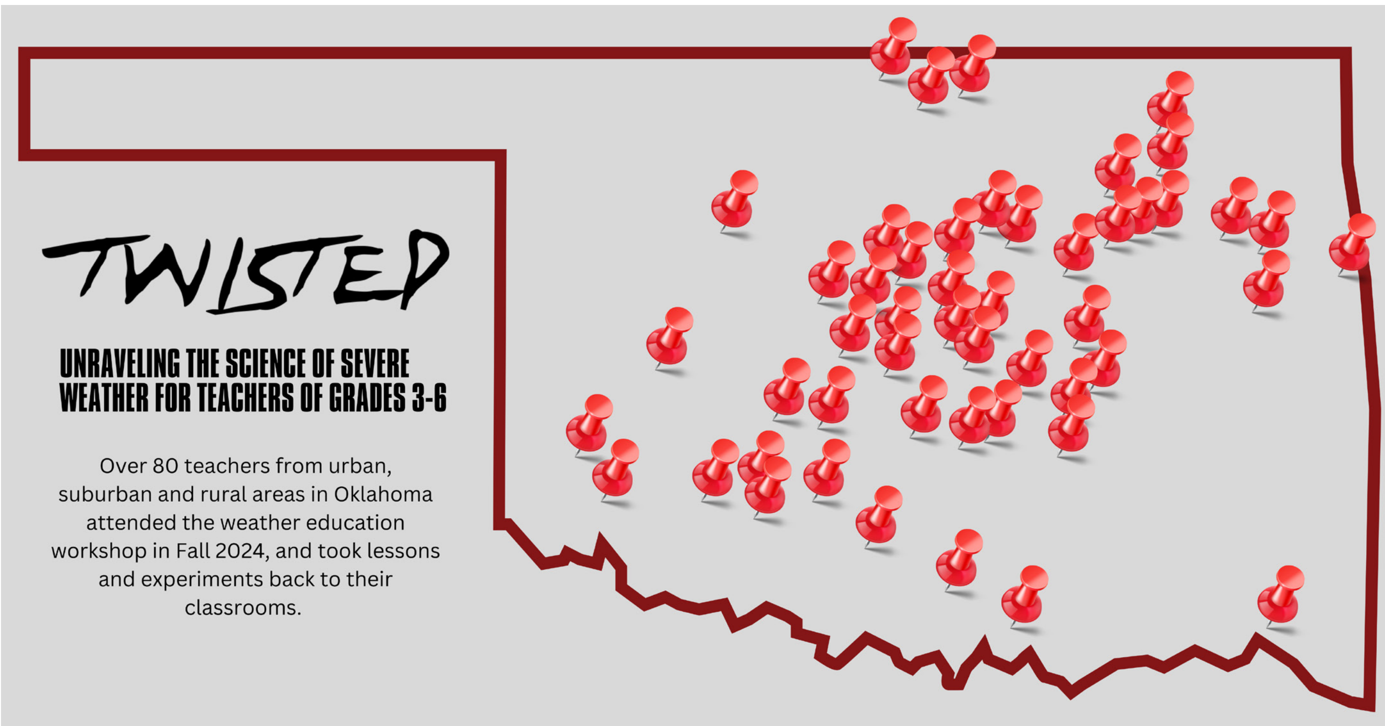


Figure 3-2: Locations of school districts of teachers attending CIWRO's educator workshop.

- **Teacher workshops:** CIWRO developed and presented a workshop for science teachers of grades 3-6 for the first time in fall 2024 through a partnership with the Oklahoma Mesonet. Although we originally planned to offer this workshop to an initial cohort of 20 teachers, 340 teachers joined the waiting list in the first two days it was announced. Due to high demand for the workshop, we repeated the workshop with a double cohort each time so that we reached over 80 teachers. The workshop was titled "Twisted: Unraveling the Science of Severe Weather for Teachers of Grades 3-6." Topics in the course included exploring the atmospheric ingredients that can spur tornadoes, learning how flooding, lightning, hail and tornadoes happen and how to stay safe, plotting weather data on maps and graph, and engaging in hands-on activities to share with students. Lunch and learning supplies were included, and schools received a $100 substitute teacher stipend when one of their teachers attended. Participating teachers also received a free STEM weather kit to take back to the classroom. Survey responses from the workshop attendees were over-

whelmingly positive. While only 58% of the teachers had taught a weather unit before attending, 99% said they were likely to teach the concepts learned at the workshop in their classes. Further, 88% of the teachers said they were likely to take the lessons back to their districts and share with other educators. Other teaching workshops with CIWRO participation included the Oklahoma Science Teaching Association Summer Conference in June 2023. Figure 3-2 shows the home school districts of teachers attending the workshop.

- **Visits to summer camps**: In addition to classroom visits and teacher workshops, CIWRO scientists directly participate in summer camps. One such example was the 2023 visit to the summer camp of the Otoe-Missouria Tribe in northern Oklahoma on "Tribal Youth Preparedness Youth Camp." Presentations at this camp focused on both the science of tornadoes, but also on steps to take to prepare for severe and hazardous weather. Due to the successful engagement with the participants (aged 12-17 years), arrangements were made for a subsequent visit of tribal youth to visit the National Weather Center to include demonstrations of the UAS vehicles and the mobile Mesonet. Other examples include CIWRO's participation in the Mesonet Summer Camp in June 2023, where scientists from WDTD gave an issue your own warning box demonstration to 9th, 10th, and 11th graders from Oklahoma.
- **Visits to after school programs**: In addition to developing content that can be delivered to after school programs, CIWRO scientists also participate in the delivery of material at some after school programs. One of our most successful ventures was the development of the "Five Nights of Eddies: Surviving Tornadoes, Hurricanes and Other Severe Weather." The STEM enrichment camp was delivered with co-funding support from the Oklahoma State Regents for Higher Education. This was presented at the Boys & Girls Club of Norman in Spring 2024 and involved five 3-hour sessions on Friday nights. Each evening consisted of a guest presentation by one or more CIWRO scientists followed by math and science lessons with interactive games delivered by a state-certified middle school teacher. Teachers worked with CIWRO scientists to ensure their lessons were accurate and relevant to severe weather. This enrichment camp was unique in that the majority of participants were performing at one to two-grade levels below average and was designed to show that everyone can pursue a career in meteorology and science. This camp received the 2024 Education and Career Development Award from the Boys & Girls Club of America's Oklahoma Area Council. Forty students were enrolled in the camp, and teens got the chance to work with 17 different scientists across the five weeks of the camp. We saw a quantifiable increase in a positive attitude toward STEM. On our pre-camp student surveys, we asked students how likely they saw themselves having a career in math: 36% said not likely – math doesn't interest me. 16% said not likely – I'm not very good at math. On our post-camp surveys, we asked the same question: Only 27% said not likely – math doesn't interest me. Only 7% said not likely – I'm not very good at math. Similarly, we asked students how likely they saw themselves having a career in science. On the pre-camp surveys: 24% said not likely – science doesn't interest me. 16% said not likely – I'm not very good at science. On the post-camp surveys: Only 13% said not likely – science doesn't interest me. Only 7% said not likely – I'm not very good at science.
- **Fairs and festivals**: CIWRO researchers visit approximately five fairs per year to promote

science education and opportunities to join severe weather endeavors at OU. CIWRO has set up STEM fair booths at Science Museum Oklahoma, the Oklahoma History Center and Geekapalooza. Multiple departments from CIWRO present their science to families at the National Weather Festival, which attracts more than 4,000 visitors each year. In addition, CIWRO is present at high school career fairs, answering questions about secondary coursework needed to major in meteorology or related fields. CIWRO also meets with prospective students at Sooner Saturday and Admitted Student Day, events sponsored by OU's College of Atmospheric and Geographic Sciences.

- **WDTD exercises**: The WDTD teams support operationally based warning and forecast exercises for high school students as well as School of Meteorology Students to learn more about how warnings are formulated and changed during time periods of severe weather.

Undergraduate education

CIWRO currently employs 68 undergraduate students and has employed a total of 130 different undergraduate students since its creation in October 2021. Many CIWRO employees advise undergraduate students in a variety of ways.

- **Research Experiment for Undergraduates (REU) Program**: CIWRO researchers regularly serve as mentors for the National Weather Center REU summer research program that pairs undergraduate students with research mentors to conduct a project in meteorology, radar engineering, geography, environmental sustainability and other interdisciplinary projects. The underlying goal of the REU program, sponsored by the National Science Foundation, is to provide undergraduate students with a chance to experience research with the hope of attracting some talented students into the research world. The program seeks to attract more than 50% of the participants from schools where research opportunities are limited, broaden participation in science and engineering, and attract the majority of students from outside OU. The students are provided with stipends, travel to/from OU, housing for the duration of the program, and participation at a national conference. Holistic program activities include skill-building workshops, career talks, science seminars and more with the goal of building a cohort of students that support each other. A number of students who participated in the REU program have ultimately pursued graduate degrees at OU, but also at other universities. The role of CIWRO employees has included acting as a research advisor, a writing coach, or as speakers and workshop leaders.
- **Hollings Advisors**: CIWRO researchers have also participated in the Ernest F. Hollings Undergraduate Scholarship program. This scholarship program provides undergraduate applicants with awards that include academic assistance for two years of full-time study and a 10-week full-time paid internship at a NOAA facility during the summer. CIWRO researchers embedded within federal laboratories have provided advisory assistance to award winners.
- **Capstone Course Advisors**: The School of Meteorology offers a senior seminar that most undergraduates take. Here senior undergraduate students undertake a research project under the guidance of a faculty or other scientist in the National Weather Center. Many CIWRO researchers have served as advisors for undergraduate students in this capstone course.

- **Summer Workshop**: CIWRO first offered a weeklong Summer Graduate Student Research Colloquium in June 2024 and has since modified the workshop for June 2025 to be a Summer Student Research Colloquium that allows participation from recently graduated students and rising seniors and juniors. No background in atmospheric science is necessary for participation in the workshop as the goal of the workshop is to provide opportunities to emerging scholars who wish to learn more about atmospheric science and how it might relate to or enhance their chosen fields of study. CIWRO covers all costs of participating students including travel, housing, meals and excursions. Students spend a week immersed in cutting-edge weather research at the National Weather Center, exploring what it is like to have a career in meteorology or adjacent fields, and are exposed to strategic skills useful to any profession that works with science. Objectives include learning about weather research, learning to give presentations to diverse audiences, and working with experienced mentors on a guided research project. Evaluation of the first 2024 workshop was overwhelmingly positive. For example, one student noted that "the colloquium helped me begin sorting through and finding the direction to my research interest."
- **Task II/Task III/External Grant Support**: CIWRO employs a number of undergraduate students who are directly supported on Task II, Task III, or externally funded proposals. There are a wide range of duties that these students undertake but generally help with the research projects of the CIWRO researchers. Many of these students have presented their work at conferences, such as the American Meteorological Society's annual meeting, and many have also published their work in refereed journals.
- **CIWRO Undergraduate Student Fund**: For nascent or emerging projects where no external funding is available, CIWRO researchers may apply for funding from the CIWRO Undergraduate Student Fund. The funding for this project, made available from Task I funding, supports independent research of undergraduate students being advised and mentored by CIWRO researchers. Students supported by this fund have presented their work at the American Meteorological Society Annual Meeting and topical conferences and have won awards for best student presentation. Work supported by this fund has also been published in refereed journals.
- **ARM Data Quality Office (DQO) Undergraduate Support**: While the ARM DQO at CIWRO has developed automated data quality assurance tools in collaboration with other scientists, the human eye is still needed to verify what our algorithms tell us or to identify issues that were missed. Given the voluminous amount of data ARM collects daily, there is too much data for the permanent staff of five scientists to visually inspect. Therefore, CIWRO hires and trains between 8 and 12 OU undergraduate students per semester to serve as student data quality analysts. They review the output of all the diagnostic tools, and file Data Quality Problem Reports when data quality issues are encountered so that the DQO staff and others can determine proper courses of corrective action to minimize the amount of poor data collected. Some students, who express interest, even help with research problems that are vexing. These activities provide students with invaluable data analysis experience they can use in their studies and beyond.
- **Mentoring Ecosystems within the School of Meteorology**: Many CIWRO researchers participate in mentoring ecosystems within the School of Meteorology. These ecosystem

support groups consist of small groups of students with a scientist leader from the National Weather Center. The ecosystems are arranged by the identification of topic areas where students who like to receive support, guidance, mentoring and community building. The ecosystem leader meets with all members of the ecosystem together once a semester and also holds individual meetings with students as needed.

- **Field Project Participation**: CIWRO conducts a lot of field work, especially in the springtime. The field work includes activities such as deployment of UAS, sounding launches in severe weather experiments, participation in collection of data by ground-based remote sensors, and tornado damage surveys. There is a strong need for assistance in this data collection, and CIWRO maintains a list of undergraduate students who are interested in getting experience with data collection and analysis. For deployments, these students are hired as undergraduate research assistants, and they help CIWRO researchers in the collection of the data. Many undergraduate students have noted that this is a highlight of their educational experience at OU.
- **OU College of Education**: CIWRO researchers have given lectures for a class to pre-service elementary science teachers. Many hands-on activities were included in the morning-long class, including looking at how temperature changes as air expands, how clouds form, and how to measure raindrop sizes in a pan of flour.
- **Camp Crimson/OU Admitted Day/OU Career Fairs**: CIWRO participates in undergraduate student events at OU. For example, CIWRO participates in Camp Crimson, which is a 5-day orientation experience giving students the opportunity to connect with the OU community and allows meteorology students to learn about research opportunities within CIWRO. A CIWRO researcher also acts as a science ambassador at OU admitted day, where admitted high school seniors and college transfers in meteorology learn about opportunities available to them in the National Weather Center. Sooner Saturday is an opportunity for high school juniors to visit the National Weather Center and interact with not only the School of Meteorology, but also with scientists from CIWRO to learn more about opportunities available for undergraduate students.
- **Sooner Competitive Robotics**: Noah Zemlin of CIWRO is a faculty advisor for Sooner Competitive Robotics, a student-led organization that competes in robotics competitions across the nation. As faculty advisor for the team, he helps make sure the team is succeeding in the team's mission: teaching their members industry-level engineering skills and creating opportunities to improve the quality of engineering throughout the state. That help usually is provided as engineering mentoring, and providing guide rails for administrative tasks. As part of building their Intelligent Ground Vehicle Competiton (IGVC) robot every year, students practice hands-on industry-level engineering skills such as CAD design, PCB design, computer engineering, and complex software engineering which includes data processing and filtering, computer vision, machine learning, and HMI design. Further, they started the Student Tele-Operated Robotics Mission (STORM) competition in 2023 to fill the need for a robotics competition in the Great Plains region. To make STORM feel unique to OU and Norman, the competition features a different weather-themed mission every year. The 2024 mission was to create search and rescue robots to assist after a severe weather event. The 2025 mission is named Hailstorm which, as the name suggests,

is themed around studying hail. Robots for this year's mission must collect "hail" as it falls through the duration of the mission and sort it based on size.

Graduate students

CIWRO currently employs 30 graduate students and has employed a total of 47 different graduate students since its creation in October 2021. Although the majority of CIWRO's graduate students are within the School of Meteorology, CIWRO also funds graduate students in the following departments: Department of Geography and Environmental Sustainability, Mechanical Engineering, Electrical and Computer Engineering, and Civil Engineering and Environmental Science. There are a few different ways in which educational opportunities are made available to graduate students.

- **Funded Graduate Research Assistants (GRAs)**: The most common way that CIWRO provides educational opportunities to graduate students is through funded GRAs. These assistantships allow both M.Sc. and Ph.D. graduate students to pursue their own research projects in one of the five thematic areas of CIWRO research so that they do not need to worry about the funding support for their project. Each student has a CIWRO supervisor who may or may not be the primary research advisor and mentor of the student. The funding for the students comes from either Task II or Task III funding, or from externally funded grants. Students have presented their research at major national and international conferences and have won many awards for the quality of their presentations. Further, much of the student work has been published in the refereed literature.
- **CIWRO Mentoring Activities**: The majority of the mentorship of the CIWRO graduate students comes from their CIWRO supervisor, research advisor and mentor, and committee members. Many CIWRO researchers are affiliate faculty at OU, regularly serving as both primary research advisor and a committee member of a graduate student. Recognizing that other mentorship opportunities can be beneficial, CIWRO also conducts some mentoring activities over the course of the year, with topics selected based on graduate student interest determined by a poll. Examples of these activities include the following: reception with CIWRO and NOAA leadership; preparation of CVs and resumes; how to present scientific seminars; how to write scientific grants, etc. Other mentoring activities and courses are also available from the OU graduate studies college.
- **Summer Workshop**: As mentioned above in educational opportunities for undergraduate students, CIWRO hosts a summer student research colloquium in June 2024 to emerging scholars who wish to learn more about atmospheric science and how it might relate to or enhance their chosen fields of study. Both graduate and undergraduate students are eligible to participate.
- **Travel to Conferences and Field Work**: CIWRO provides funding for graduate students to travel to national and international conferences, and for participation in field work. This is an important component of graduate students' educational experience.

i. Are these activities coordinated with other NOAA education/outreach programs in the area?

Many of these activities are coordinated with those of the NOAA units. For example, the summer student research colloquium is jointly organized by researchers from NSSL and from CIWRO. The speakers and mentors from the workshop are from NSSL, CIWRO, SPC, WDTD, as well as from the School of Meteorology. Although undergraduate and graduate students are supervised by CIWRO researchers, many researchers at NSSL and SPC serve as mentors and advisors for the students, as well as serving on the students' advisory committees. All participation of CIWRO researchers in working with Hollings undergraduate students is done in collaboration with federal scientists. And funding for the graduate and undergraduate student opportunities mostly originates from NOAA sources.

ii. How does the university make curricula, study guides, guest speakers, and teaching materials available to support these activities?

Graduate and undergraduate students take courses for their B.Sc., M.Sc., and Ph.D. degrees. All curricula and study guides for these courses are available on a Canvas page for each course, through which all enrolled students have access. At the NWC, there are many guest speakers throughout the year. All seminars are open to all, and each seminar is advertised through an email list distributed to occupants of the NWC and made available online.

CIWRO's meteorology curriculum for middle school students, being developed in collaboration with the Tulsa Regional STEM Alliance, will be available for free on-line once it is vetted by 12 trial schools in the 2025-2026 time frame. All module content will be finalized by 30 April 2025 and ready for teachers in digital form for the 2025-2026 school year. Print-ready versions of all modules will be released in the summer of 2025. The Tulsa Regional STEM Alliance is going to help market the curriculum, and a presentation about the curriculum will be given at the 2026 Annual Meeting of the American Meteorological Society.

b. What are current and planned outreach efforts?

CIWRO has many past, current, and planned outreach efforts as explained in the sections below.

Public outreach

There are a number of different mechanisms by which CIWRO engages in public outreach.

- **National Weather Festival**: Each fall (typically October), the NWC opens to the public for the National Weather Festival which annually attracts more than 4,000 people. It is a fun and free event with exhibits and demonstrations not only from the weather-related organizations with the NWC but also includes attendance from broadcast meteorologists from local news channels, local emergency managers, and helicopters. CIWRO has a heavy presence at the National Weather Festival, with demonstrations of our UAS, our Collaborative Lower Atmospheric Mobile Profiling System (CLAMPS) trailer, and from CIWRO researchers

on how to implode an aluminum can, measure the sizes of raindrops with flour, and how to effectively communicate watches and warnings.

- **Participation in Community Events**: There are frequently STEM community events in which CIWRO participates. These events have included participation in Severe Weather Preparedness Day at the Science Museum of Oklahoma, a STEAM night at the Oklahoma History Center, the Oklahoma Electrical Cooperative, Family Metro Magazine's Geekapalooza and many other such activities.
- **Tornado/Severe Weather Museum Exhibit**: In cooperation with NOAA, we have supplied the Oklahoma Hall of Fame Museum with artifacts and interviews to create a severe weather exhibit in its Oklahoma City location. After meeting with museum curators, they requested help with a "Women in Weather" portion of the exhibit. We collected profiles of outstanding scientists who work in the NWC and are awaiting the unveiling of the exhibit.
- **CIWRO on-line science lessons**: During the pandemic, it was necessary for CIWRO to curtail in-person activities. Thus, CIWRO presented a number of on-line science demonstrations that are now available as YouTube videos (Educational Videos). Topics include "Whirling Weather", "Clouds in the Kitchen," Cooking up a Storm," and "Snow, Hail and Graupel.
- **Skype a Scientist**: CIWRO researchers have previously volunteered in the Skype a Scientist program, where researchers are connected with classrooms, families, libraries, Scout troops and many others. This gives students and the public an opportunity to get to know a real scientist and have their questions answered.
- **Citizen Science Program mPING**: CIWRO operates the citizen science mPING (Meteorological Phenomena Identification Near the Ground) program that allows students of any age and the public to be a weather observer while learning about the atmosphere. Public weather reports are collected through a free app available for smart phones or mobile devices. These reports are immediately archived into a database at OU and are displayed on a map accessible to everyone. To use the app, reporters select the type of weather that is occurring and tap 'submit.' Anonymous reports can be submitted as often as every minute.
- **Mentorship of students in robotics competitions**: CIWRO employees mentor Team OKC, a club made up of high school students who participate in the FIRST Robotics Competition. In their workshop housed in at the Science Museum of Oklahoma, the students design robots to solve problems and have recently traveled to the world championship in Houston, Texas. In this activity, members of Team OKS log about 12 to 20 hours a week for 12 weeks starting in January to design a 150-pound robot to compete in that season's game, which is played by robots in a three-on-three competition on a basketball court-sized area. The team uses a computer-aided 3-D modeling program to design the robot, which starts out as a drive base that resembles a large Roomba. It is up to the students to customize the robot with apparatus to score points in the game.

Professional training

CIWRO supports the NOAA mission by supporting the training of NOAA employees, including forecasters and other personnel as documented in the Forecast Applications Improvement

description of accomplishments for Theme III. Examples of the professional training provided include the following:

- **Radar and applications course:** This course consists of over 100 hours of training on radar principles and is made up of over 150 learning objects, of which 90 have been produced or updated by CIWRO employees since October 2021. Since CIWRO was formed, 455 NWS forecasts have been trained, representing 20% of the operational workforce.
- **Warning operations course (WOC) - winter:** This course consists of 30 hours of training material designed to improve the performance of NWC offices in issuing watches, warnings, and advisories during winter events. It has had over 500 NWS participants since CIWRO was formed, and CIWRO employees have authored 17 new lessons, updated 11 lessons and begun developing a new WES-in-the-Cloud simulation for FY2025.
- **Warning operations course (WOC) - flash flood**: This course provides NWS meteorologists and hydrologists with the latest tools and topics related to flash flood warning decision-making. It consists of 19 hours of online training materials. Of the 44 modules, CIWRO employees have authored 21 modules. Since 2021, CIWRO employees have created 15 new training modules and significantly updated 5. There have been 3200 NWS user completions since October 2021.
- **Warning operations course (WOC) - severe**: This course is designed for NWC meteorologists to improve their ability to issue severe thunderstorm and tornado warnings. There have been 326 completions since October 2021. CIWRO employees have authored 17 new lessons, updated 10 lessons, and graded over 250 hand analysis assignments since October 2021.
- **Warning operations course (WOC) - human factors**: This course focuses on critical topics regarding the human element of warning decision-making and has been facilitated and led by a CIWRO employee since August 2022. The course consists of 9 hours of training. Since October 2021, 617 NWS forecasters from 127 different offices have enrolled in the course. CIWRO employees authored 13 lessons, significantly updated 6 lessons, and graded over 300 user assignments.
- **Storm of the month webinars**: These webinars highlight both current operational best practices and new procedures for experimental products planned for operational use. CIWRO staff have led 21 webinars since CIWRO was formed and have been sole content presenters 5 times. Over 1300 forecasters have registered for these live webinars, and 3300+ completed watching recorded YouTube versions.
- **Research-to-operations and operations-to-research webinars**: This webinar series raises awareness amongst NWS meteorologists of experimental tools and techniques being used to help issue short-fused warnings. Five webinars have been orchestrated by CIWRO staff since 2023. The live webinars roughly reach 175 individuals, and recordings on YouTube have reached 300 views.
- **AWIPS build training**: The Advanced Weather Interactive Processing System (AWIPS) is the NWS software for data visualization, forecasting and issuing warnings. When a new build is released, CIWRO staff develop user training based on the most significant updates, which

usually consists of a short video lesson and supplemental jobsheets for hands-on practice. Since October 2021, CIWRO staff have supported two AWIPS build release and one emergency release producing one video, five jobsheets and updating the dedicated VLab build training webpage. The most recent training video and jobsheet has been completed by 940 NWS employees.

- **AWIPS fundamentals**: AWIPS fundamentals training is part of the required Radar and Applications Course (RAC), where new NWS forecasters learn to use AWIPS as applied to the course goal of radar interpretation and issuing convective weather warnings. Since October 2021, CIWRO staff have tracked the progress of nearly 400 NWS forecasters from all 122 Weather Forecast Offices (WFOs). CIWRO staff are now overhauling AWIPS Fundamentals into a standalone Fundamentals of AWIPS course.
- **New NWS training officer (SOO/DOH) development course**: This course is normally held every 2 to 3 years with a residence component at the NWS Training Center (NWSTC) in Kansas City. Courses were held in 2022 and 2023. For example, in 2023, CIWRO staff participated on-site at NWSTC in a panel discussion about the transition from the physical Weather Event Simulator (WES) to the cloud-based WES.
- **Radar Operations Center (ROC) collaboration and WSR-88D build training**: CIWRO supports this training by attending periodic meetings with the ROC to learn about significant changes in software updates, get access to preliminary versions of the software, and provide feedback to WDTD instructors that can be included in the training for the radar update. Since October 2021, CIWRO staff have participated in three cycles of radar build software and hardware updates, which have resulted in over 2700 completions by NWS forecasters.
- **Cloud Automated Scheduler (CLAS) for training activities**: Because not all cloud-based training activities can be supported by the current cloud-based WES, CIWRO has created CLAS for forecasters to schedule and access training so that forecasters can schedule and access training 24 hours a day. CLAS has already supported at least 2,625 individual and unique training instance requests.
- **AWIPS cloud archive of weather events for training and research**: Because a cloud-based WES requires an archival system, CIWRO developed and maintains a 30-day rolling cloud-based archive of data from AWIPS to populate an ongoing case repository. CIWRO has also guided NWS staff to upload some 600 existing case events and simulations to the Cloud to form a library.
- **Post-storm damage survey training**: This course consists of 9 lessons on how to use the Damage Assessment Toolkit (DAT), ranging from how to use the tool to how to create tornado damage swaths and perform flash flood surveys. The course has received over 5700 individual lesson completions.
- **Hazard services warning generation tool training for NWS users and focal points**: CIWRO staff have developed training on hazard services including modules, jobsheets, cloud instances and reference sheets. A NOAA-provided web service, called VLab, is used to host and distribute written training materials along with links to video training on YouTube.

- **Probabilistic impact-based decision support services (IDSS) training and support**: CIWRO staff have created job sheets for best practices associated with the use of the Graphical Forecast Editor (GFE) tool which generates gridded forecast products disseminated to the public. CIWRO staff have also developed a new course teaching forecasters the fundamentals of probabilistic forecast products, entitled Ensemble Fluency which consists of 27 separate lessons. AS of January 2025, 1764 completions have been recorded with several hundred other forecasters competing a subset of the material.
- **NWSTC support for NWS decision support and communication services:** The NWSTC has developed e-learning courses for Decision Support Training that have been completed by 400 employees and have assisted in updating several other courses int he series. NWSTC has also provided training to NWS employees to communicate with emergency managers, the media, and community leaders.
- **NWSTC support for the NWS leadership academy**: NWSTC supports NWS Foundations, an introductory course for NWS new hires by conducting webinars and 3-day residence courses, provide resources, interpersonal training and awareness of policies and norms of the NWS and NOAA, and transition content to best format for virtual or live delivery. Since 2020, 1109 people have participated in NWS foundations (25% of the NWS).

i. Does the CI conduct joint outreach with other NOAA funded or supported activities?

As listed in section 3.a.4, many of our educational and outreach activities are joint with other NOAA funded or supported activities. For example, the National Weather Festival includes contributions from NSSL and SPC. Our outreach committee meets jointly with the NSSL outreach committee at least twice a year to discuss collaborative projects, including not only outreach events but also educational events. When appropriate, joint activities result.

ii. What are the current or planned efforts with non-academic partners (i.e., non-profits or private sector engagement)?

As described in Section 3.a.1, CIWRO partnered with the Tulsa Regional STEM Alliance to develop curriculum for middle school students. We have a planned collaboration to develop a tornado/severe weather museum exhibit with the Oklahoma Hall of Fame. We have participated in several outreach events at places like the Science Museum of Oklahoma and the Oklahoma History Center and will continue to participate in such planned events on science days or severe weather preparedness.

iii. What are the current planned efforts for community outreach, where appropriate? Underserved and frontline communities?

Our current planned efforts for community outreach have been described above. We will continue to participate in these activities yearly.

4. SCIENCE MANAGEMENT PLAN

a. How does the Institute identify new intellectual opportunities?

Even though all CIWRO personnel are funded to work on specific projects, we have developed a number of mechanisms whereby new intellectual opportunities can be identified. There are further articulated below.

Professional Development Time: Although the majority of CIWRO employees' time needs to be spent on the projects CIWRO is funded to work on, CIWRO recognizes that it is critically important that all employees have some dedicated time for professional development. Thus, all employees are expected to dedicate 10% of their time to professional development, and this is formally documented in performance plans. Professional development is defined as initiatives aimed at enhancing the skills, knowledge and career growth of the employee and others, fostering continuous improvement and expertise within the organization. Many employees use their professional development time to branch out into new areas of research and use the results of this research to identify new intellectual opportunities. As a result of the knowledge gained, this helps CIWRO to identify proposals to write and receive more funding for research or can lead to discussions with NOAA program managers to increase Task II or Task III funding in specific topic areas. It is also possible conference presentations or written manuscripts can emerge from the professional development time, bringing these new intellectual opportunities to fruition.

Directors Discretionary Research Funds (DDRF): Every spring, CIWRO offers a competitive internal grant called the DDRF. These are small grants (typically ranging from $10 - $40K) that are valid for 12 months. The purpose of the DDRF is to seed nascent, exploratory, or otherwise unfunded research activities conducted by CIWRO researchers. CIWRO is particularly interested in funding high-risk projects that have a high-potential payoff (i.e., may lead to significant advances for CIWRO and/or future funded research projects). Projects that identify new transformative ideas with potential societal applications are specifically targeted for funding, as these are the new intellectual opportunities that might lead to significant long-term funding. Criteria used for evaluating applications to this fund are as follows: qualifications of the proposers to successfully complete the work in the time allotted, the scientific and technical merit of the proposed work, the potential for future innovation, and how well the project addresses the scientific priorities and focus areas of CIWRO. In the last cycle, projects increasing collaborations between consortium partners were specifically targeted. Funding for the DDRF fund originates from the sponsored research initiative (SRI) funds that are returned to CIWRO, based on a percentage of the funding that CIWRO brings to the University. Examples of previous projects funded in recent years include the following: i) examining the use and effectiveness of NWS fire warnings during the 2024 Southern Great Plans wildfire outbreak of 26 and 27 February 2024; ii) viewer preferences for next- generation media content during hazardous weather; iii) creating a new gridded snow product using impact-based verification; iv) electric field sonde for thunderstorms – instrument design; v) exploring meaningful ways to convert uncertainty in precipitation type output into probabilistic output using the WINTRE-MIX field campaign data; vi) implementing a National Weather translation program

through AI, GIS and risk communication; vii) exploring how urban heat islands can affect winter precipitation type in support of UAS and Urban Air Mobility (UAM); viii) precision landing and auto-charging for weather-sensing UAS; ix) weather salience among bilingual Hispanic and Latinx populations in the United States: evidence for culturally competent communication; x) exploring the relationship between Flash Flood Severity Index (FFSI) and the Flooded Locations And Simulated Hydrographs (FLASH) project using detailed flash flood surveys; and many others.

Workshops on Emerging Scientific Thematic Areas: CIWRO regularly holds and hosts workshops on topics that are identified as emerging scientific themes by the Director or any CIWRO employee who chooses to propose a workshop. The idea of the workshops is not to replicate scientific conferences where there are series of short presentations, but rather to bring together diverse groups of researchers to discuss new intellectual opportunities in specific topic areas and challenges to making progress on solving scientific problems in those topic areas. The workshops are typically three days long. The first day consists of a series of invited talks that describe significant advances that have been made in the topic area, remaining issues that need to be solved in order to make further advances in the topic area, challenges or impediments that remain to be solved, and additional knowledge, tools, observations and models that are needed to address those challenges. These are designed to be overview talks of the subject matter rather than highlighting the work of a single investigator presenting the talk, but each topic is covered by multiple speakers in order to hear a diversity of opinions. The second day of the workshop is entirely dedicated to small group breakout sessions, where the groups are challenged to identify what is hindering progress in the topic area, key sources of uncertainty and how they can be reduced or minimized, and identification of tools, models, observations and resources needed to address those challenges. The third day of the workshop is dedicated to a summary of the breakout discussions and an overarching discussion of future directions. Some shorter duration workshops have had some differences in format, but the overarching goal is always to identify new opportunities, and strategies for addressing those opportunities. Participation is sought not only from CIWRO researchers and consortium partners, but also from other members of the NWC in Norman Oklahoma as well as externally funded participants, especially those who bring expertise not currently within CIWRO. Several of these workshops have been held, with the most recent being the October 2024 “Workshop on Science, Predictability, Operations, and Response for High-impact Weather” held at the consortium partner the University at Albany. Other workshops have included the February 2024 Workshop on Fire Weather and Forecasting and workshops on each of the five CIWRO themes. These thematic workshops were designed to bring together researchers at the consortium partners, OU, and federal partners. The output of these workshops has included overview papers in the *Bulletin of the American Meteorological Society* (e.g., McFarquhar et al. 2021), the development of white papers describing future research directions, and the assembling of small teams to either perform research or write research proposals to gain funding for some of the ideas developed in the workshops.

Attendance at Professional Conferences and Networking: CIWRO researchers need to be aware of research projects being worked on by researchers at other institutes across the nation and around the world. Further, they need to have discussions with researchers with

multiple viewpoints not necessarily represented within CIWRO itself. Thus, CIWRO highly encourages its employees to attend national and international meetings to not only present their own research, but also to learn from the research of others and engage in conversations in future research directions. The majority of CIWRO employees attend at least one conference a year, and many researchers attend more than one conference every year. Funding for conference travel is typically included in task II, task III, or external proposal funds. CIWRO also maintains a travel fund, supported by SRI return from OU, where CIWRO researchers can request funds to attend a conference for which they otherwise do not have funding. Applications for this funding need to explain how attendance at the conference would benefit the applicant, as well as showing why their attendance would be beneficial to CIWRO.

Developing Proposals in Response to Solicitations: Recognizing that funding is required for CIWRO researchers to engage in new intellectual opportunities, CIWRO encourages its employees to seek external funding when appropriate (i.e., falling within one of our five themes) and when synergistic with activities already ongoing at CIWRO. Since federal funding opportunities are frequently targeted at new intellectual opportunities, this is a natural way for CIWRO researchers to engage in these opportunities. There are some procedures that must be followed when developing these proposals. First, the proposal must fit within one of the five themed areas of CIWRO research. Further, employees who wish to use federal assets (including office space, laptops, data, etc.) in the development and execution of the grants must seek and obtain federal concurrence from their federal leadership prior to submission. CIWRO has a formal procedure by which this concurrence is requested. Further, CIWRO must ensure that any funded research priorities will not be negatively impacted when employees engage in these new targeted opportunities.

Prompt Response to Other Targets of Opportunity: CIWRO has a small leadership team (Director, Associate Director, Assistant Director, Executive/Financial Director) that allows it to rapidly respond to any opportunity that emerges to identify and address new intellectual opportunities. One recent example of this is the development of the UAS program within CIWRO. Before 2021, OU was home to the Center of Autonomous Sensing and Sampling (CASS), which consisted of an interdisciplinary team of scientists and engineers working on the development and implementation of novel autonomous solutions for environmental sampling, and especially the use of UAS. When the Director of CASS left OU, all of the engineering and personnel assets were in danger of being permanently lost. CIWRO was quickly able to propose and bring the UAS program within its umbrella so that access to these resources and their ability to contribute to NOAA's mission was not permanently lost. The small, fast-response nature of CIWRO's leadership team allows for the identification of new intellectual opportunities.

i. What is the university's policy on licensing/patenting intellectual property?

OU has an Office of Technology and Commercialization (OTC) to assist university investigators in protecting intellectual property and inventions (patents). A complete description of the university's policy on patents and intellectual property is available at https://www.ou.edu/research-norman/research-services/guidance/patents-intellectural-property. For sponsored projects, the need for protection on intellectual property is disclosed before the submission

of the proposal in order to protect intellectual property rights, and as part of the award close-out process, the Principal Investigator (PI) submits a patent report through coordination with OTC.

During the life of a proposal, any technology invention is to be reported to the OTC and assigned a Technology Invention Number. Then a meeting is set up between the Managing Director of OTC, the Director of Intellectual Property, the Technology Transfer Administrator and the PIs to discuss patenting, commercialization and licensing options and the processes for pursuing them. Some recent examples of technology developed at CIWRO that have followed/are following this commercialization process are “A Data Compression Method for Radar Based on Non-Uniform Quantization” and an “Enhanced UAS-based Vertical Atmospheric Profiler.”

The Intellectual Property Policy of OU is available at https://www.ou.edu/content/dam/old/docs/2016-2017/IP%20Policy%2010.16.pdf. It is explicitly stated that “the creation and development of intellectual property at the University encourages new business and is key to creating strong University and industry partnerships,” and that ‘intellectual property development shall be pursued in concert with, but subject to, the University’s principal responsibilities of education and knowledge creation.” The University works to ensure that “creators of copyrightable works or trademarks and inventors share in any financial success enjoyed by the University through the creation and commercialization of intellectual property” subject to the following objectives: “1) To maintain the University’s academic policy of encouraging research, publication and scholarship independent of potential gain from royalties or other income; 2) To make patented materials created pursuant to University objectives available in the public interest under conditions that will promote their effective utilization and commercialization; and 3) To provide adequate incentive and recognition to faculty and staff through proceeds derived from their creative works, trademarks, discoveries and inventions.”

With regards to patents, “all discoveries and inventions …including any and all patents…which are made or conceived by any member of the faculty, staff, or student body of the University of Oklahoma … shall be owned by and be the property of the Board of Regents of the University of Oklahoma.” The document also describes how the revenues “received by the University directly attributable to the licensing, sale, or commercialization of a university discovery or invention” will be distributed between the inventors and the university. More details are in the aforementioned documents.

ii. What barriers exist to successfully transition research products into commercial applications?

The barriers that exist are somewhat dependent on the specific research project that is being transitioned into commercial applications, but nevertheless some general comments can be made. The main issues center around how the work dynamics, time allocation and resources are divided between the inventors at CIWRO and the industry partner. One key barrier is the challenge of securing adequate funding to cover the time and effort required for commercialization. This is especially difficult when commercialization is not an anticipated outcome of the original work as is often the case with certain funding agencies. For example, a CIWRO

employee recently asked if they could use Task II funds to support the effort involved in commercializing a technology that was developed during a research project, something that could consume a significant portion of the employee's time. While this may not always be a significant barrier, and in some cases CIWRO can cover the time needed in a similar way as to how we allocate resources for publishing research papers, it needs to be better addressed how commercialization efforts can be explicitly funded within project structures.

Another barrier can be in funding for prototyping and scaling of a project, such as a drone being developed under our UAS program. In general, researchers do the initial development and proof of concept, but this does not imply that the deliverable or prototype is fully refined for scaling and commercialization. Within the context of the development of a drone, an industry partner may want to study how the drone can withstand "abuses" of a typical user, and sometimes this requires design changes while trying to keep the initial concept functioning. There is no clear line in whether the inventor or industry partner should be in charge of these changes, and this involves nontrivial negotiations on the proper use of funds and resources.

One more barrier applies to user training and support needs. Partners typically require training on the intellectual property that has been developed, and this takes the time of researchers. Since this can amount to more than a trivial amount of staff time, it is unclear how this funding should be covered since it appears that IP transfer/training costs are not always included in the negotiation for IP licensing.

iii. How does the CI account for successful research to operations/intellectual property development activities in its financial record keeping?

OU employs an Office of Technology Commercialization, which oversees the invention disclosure and/or patent process (https://www.ou.edu/otc). OU works in coordination with the federal government for disclosure of jointly developed products to allow for government usage and follows all applicable laws and regulations for licensing to outside entities. Royalties for any patented products are sent to CIWRO in a separate account from research dollars and are used to support continued research in the applicable fields and supporting future research.

As Task II projects are transitioned to operations, CIWRO coordinates with NOAA to determine if there is continued research in these areas for future development or if this research line is now complete. For research objectives that have fulfilled their lifespan, CIWRO does not request any further funding on the Task II project and reallocates research staff time to projects that are identified as priorities for NOAA. For projects that have continued research priorities, CIWRO works with the NOAA funding line office to update research priorities and project narratives (if needed) to transition to the next phase of research.

iv. How and when does the Institute share environmental data collected/created by PIs?

Although CIWRO employees are involved in collaborative efforts with federal partners in collecting and creating data, most of the data created are owned by the federal partners and hence they are responsible for the sharing of the data.

For example, CIWRO researchers have played and are playing a major role in the development and evolution of the MRMS project. MRMS uses an automated system that rapidly integrates data from multiple radars and radar networks, surface observations, and numerical weather prediction models to generate seamless, high spatio-temporal resolution mosaics. The operational product viewer is available at https://mms.nssl.noaa.gov/qvs/product_viewer. MRMS has been operational for over 10 years at NWS, and several teams at CIWRO over the years have contributed to the successful R2O transition and enhancements which have made MRMS such a key system used and relied on by so many. Thus, whereas NSSL is responsible for the sharing of the data themselves, CIWRO plays a major role in developing the system that allows these data to be displayed.

Datasets collected from observational field campaigns are stored and published in accordance with funding agency guidelines, typically hosted and made publicly available via the National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL) Field Data Archive. Examples of datasets shared in this way include Electric Field Meter (EFM) data and Lightning Mapping Array (LMA) collected during the NSF Lake Effect Electrification (LEE) project and mobile Lightning Mapping Array data collected during the Propagation, Evolution, and Rotation in Linear Storms (PERiLS) campaign. The CIWRO ISG team has also contributed to long-term Oklahoma Lightning Mapping Array and mobile NSSL Lightning Mapping Array data collection and archival. Each dataset is published with an individual DOI and hosted publicly on an NSSL Thematic Real-time Environmental Distributed Data Services (THREDDS) server. Datasets are also published to align with open data standards for publication. Accordingly, Long Wavelength Array observations of lightning are published with a DOI and publicly available on Zenodo.

Data collected by CLAMPS are processed, stored, and archived locally at NSSL. Most data are made available in near real time on the NSSL THREDDS server provided there is enough cellular bandwidth to transfer the data. Quicklooks of the real time data are also made available on the CLAMPS webpage to monitor the health of the system and to provide a method to quickly interrogate data quality. Post campaign, data are further quality controlled and research-grade retrievals are performed when applicable. These are uploaded both to the NSSL THREDDS server and to the project data repository (e.g. EOL, ARM Data Portal, etc.).

Preliminary data from the CopterSonde are made available in real time on wxuas.com (while the UAS is still flying!). These data are stored in the cloud and can be routed to end users for data assimilation, forecast visualization, or quality control. If the flights are occurring as part of a funded field campaign, the full resolution flight logs are post processed and quality controlled to ensure high levels of data quality. The resulting research-grade files are shared on the NSSL THREDDS server and/or the applicable project data repository.

CIWRO researchers collaboratively operate federally owned radar assets to collect weather radar data in support of a variety of research objectives. For example, NSSL maintains and operates several research radar systems, including the S-band dual-polarization KOUN radar, the S-band dual-polarization Advanced Technology Demonstrator phased-array radar (https://nssl.noaa.gov/tools/radar/atd/), and the X-band dual-polarization NOXP mobile radar (https://nssl.noaa.gov/tools/radar/mobile/). In compliance with NOAA data management policies, NSSL maintains a public radar data repository (NSSL Data Repository (PARR)). Radar

data are typically available no later than two years after the data are collected.

CIWRO also participates in field campaigns funded not only by NOAA, but also other agencies. Data from these campaigns are made available on publicly accessible websites within one year of the completion of the campaign. Examples of recent campaigns where data have been made available include the NSF-funded Experiment of Sea Breeze Convection, Aerosols, Precipitation and Environment (ESCAPE) and the Cold Air Outbreak Experiment in the Sub-Arctic Region (CAESAR) field campaigns available at https://www.eol.ucar.edu/data-software/eol-field-data-archive. CIWRO also makes routines available that process data collected by aircraft during field campaigns, such as processing codes for determining cloud microphysical properties from optical array probes installed on aircraft (McFarquhar et al. 2018, https://github.com/weiwu5/UIOOPS) and for automatically determining the number of modes in observed size distributions (Brechner et al. 2023, https://github.com/PeterBrechner/Multimodailty).

Data collected through the mPING project are archived at OU. mPING is an example of citizen science that collects information about the weather at the ground from the public through their smart phones or mobile devices. The reports are immediately archived into a database at OU and displayed on a map accessible to anyone.

b. What are some recent examples of data sharing?

Examples of data sharing are provided in Section 4.a.iv. above.

c. How does the Institute monitor and encourage compliance with public access policies and plans?

CIWRO maintains strict adherence to both the academic integrity policy of OU (https://www.ou.edu/integrity) and to NOAA data sharing guidelines (https://nosc.noaa.gov/EDMC/documents/EDMC_PD-Data_Sharing_Policy_v1.pdf) and scientific integrity process (https://www.noaa.gov/organization/administration/nao-202-735d-2-scientific-integrity). In brief, CIWRO dictates that the results of all funded research must be open and publicly accessible in accordance with the data sharing policies of NOAA and whatever other agency might be funding the research.

CIWRO enforces compliance in a number of ways. Proposals that are submitted through the Cooperative Agreement must have formal data sharing and management plans, some of which can be as simple as stating that there will be adherence to the NOAA data sharing guidelines and others which provide more details on how data sharing will adhere to the guideline of the specific funding agency. All submitted publications are vetted by the CIWRO Associate Director to ensure compliance with the CIWRO publication policy. Further, CIWRO performs checks twice a year to ensure that publications with a CIWRO lead or co-authors are included in our list that is supplied to NOAA as part of our annual report. Further, any publications that use funding from our largest sponsor NSSL are included in the list of NSSL publications.

Thus, CIWRO data stewardship ensures that work sponsored by NOAA or other partnering agencies is discoverable, accessible and reusable in the longer term. As NOAA public access policies and plans change over time, the CIWRO policies will change accordingly.

d. What are your strategies to make federally funded publications, data, and other such research outputs and their metadata are findable, accessible, interoperable, and reuseable to the American public and scientific community in an equitable and secure manner?

In addition to ensuring that applicable public access policies and plans are followed, CIWRO is committed to making the data, software, and documentation supporting published research as open and accessible as possible in accordance with the FAIR (Findable, Accessible, Interoperable and Reusable) principles (Wilkinson et al. 2016). As many CIWRO papers are published in journals of the American Meteorological Society, CIWRO follows the American Meteorological Society data and software policy guidelines on publications submitted to any journal (https://www.ametsoc.org/index.cfm/ams/publications/ethical-guidelines-and-ams-policies/data-and-software-policy-guidelines-for-ams-publications. Unless there is some compelling reason otherwise, all data used in a publication must be made available before the paper is published.

e. What are some recent examples of intellectual opportunities?

In this section, only a few of CIWRO's most recent intellectual opportunities are summarized.

Threats in Motion (TIM) is a major update to operational severe weather and tornado warnings. It is a warning generation approach that enables NWS to advance severe thunderstorm and tornado warnings from the current static polygon system to a rapidly updating warning polygon that moves forward with a storm and is the first stage of implementation of the Forecasting a Continuum of Environmental Threats (FACETs) paradigm for severe weather warnings. Much work in CIWRO has concentrated not only on the development of the TIM system, but also in testing its implementation in the HWT and in the communication of information. For example, in October of 2021, an HWT experiment was conducted with emergency managers and broadcast meteorologists. During this experiment, researchers showed participants erratic spatial movements of TIM and asked for feedback on how TIM could impact operational workflows. Results showed that both partners were optimistic about TIM, but had some concerns about how it may operate at the local level. For instance, EMs noted that as the warning polygon moved, locations could get "pulled" in and out of a warning multiple times, which the public might find confusing and inconsistent (Maciag et al. 2025). Current work is determining how many emergency manager operating systems, such as tornado sirens and wireless emergency alerts, will have to be reconfigured to handle moving warnings.

mPING is an example of citizen science by crowdsourcing weather reports. It is a project de-

veloped through CIMMS/CIWRO in partnership with NSSL to collect weather information from the public through their smart phone or mobile device. The reports are immediately archived into a database at OU and displayed on a map accessible to anyone. mPING is important because it provides data at the ground, which the operational weather network cannot see and hence allows forecasters at the NWC to fine-tune their forecasts. There are other applications as well, as the data can be also used to develop new radar and forecasting technologies.

The inclusion of UAS equipment and intellectual capacity within CIWRO is another example of an intellectual opportunity within CIWRO. In particular, the CopterSonde is a weather-sensing UAS designed at OU that is being commercialized by InterMet Systems. The CopterSonde measures temperature, humidity, wind speed and direction, and pressure at high vertical resolution. Prior versions of the CopterSonde have been largely tailored for atmospheric boundary layer studies, and it has been shown to be one of the more accurate weather-sensing UAS in the research community (de Boer et al. 2024). Before 2021, OU was home to the CASS, which consisted of an interdisciplinary team of scientists and engineers working on the development and implementation of novel autonomous solutions for environmental sampling, and especially the use of the CopterSonde and other UAS. When the Director of CASS left OU, all of the engineering and personnel assets were in danger of being permanently lost. CIWRO used indirect cost returns and a cost-match account from the Office of the Vice President of Research and Partnerships (VPRP) to fund the UAS/CopterSonde program until that time there was more funding available from NOAA and external grants to support a Research Scientist and students working with the technology. In this way, these resources and their ability to contribute to NOAA’s mission were not permanently lost. Recently, the CopterSonde technology has been used in field projects, and the continued development through the Progressive Research and Optimization of a Durable and Independent Generation of Uncrewed Aircraft Systems (PRODIGEE-UAS) is improving the performance envelope of the CopterSonde and advancing ground station software to increase safety for beyond visual line of sight (BVLOS) operations.

The WoFS is a forecast system that relies on guidance from high-resolution computer models to improve forecasts, warnings, and decision support for high-impact thunderstorm events within the watch-to-warning time frame, 0 to 6 hours in advance of an event. It earned the Department of Commerce Gold Medal award in 2024 in recognition of the scientific and engineering excellence required for the development of this revolutionary prediction tool. It is also an important component of the FACETs program. However, its development is not complete, and ongoing development represents another intellectual opportunity, and it is an important component of a draft roadmap to achieve NOAA’s Artifical Intelligence for Weather Prediction (AI4WP) goals. WoFSCast uses the artificial intelligence Numerical Weather Prediction (NWP) emulator Google DeepMind’s GraphCast in an attempt to further revolutionize weather prediction by providing more skillful forecasts at much less computational expense. WoFSCast is being trained using archived forecasts from WoFS and current efforts within CIWRO are evaluating its performance. Preliminary work suggests WoFSCast closely emulates the WoFS environment fields, matches 70 to 80% of WoFS storms out to 2 h forecast times, and suffers only modest blurring. These early results out of WoFSCast suggest that AI4WP can be extended from global scale phenomena to rapidly evolving, small-scale, phenomena like thunderstorms. An enhanced focus on WoFSCast and newly started direct observations

to prediction work within the NWS Environmental Modeling Center are likely. Ongoing work is also exploring a transition to an ensemble-based framework, incorporating higher 1 km resolution into training and developing a complementary data assimilation scheme.

14-16 Fire Weather/Tornado Event: WoFS supported NWS Forecast Operations by running continuously for 49 hours with two domains 14-15 March 2025 covering a significant wildfire and tornado outbreak, and three domains 15-16 March covering tornadoes and flash floods over LA, MS, and AL to assist in saving lives, property, and minimize economic impacts to communities. There were over 130 wildfires centered over Oklahoma on 14 March aided by extreme winds and dry conditions behind an intense storm system. The fires destroyed over 300 homes and burned over 170,000 acres causing 4 deaths and over 200 injuries. The same storm system produced a historic tornado outbreak over two days impacting the Mississippi Valley and Deep South with over 150 tornadoes resulting in 24 fatalities, and flash flooding. As efforts to integrate WoFS runs into OSTI have yet to be completed, CIWRO and NSSL worked with the OSTI WoFS Administrator to set up and execute runs to improve NWS forecasting of this event. Early in the week, recognizing the potential for a high-end severe weather event 14-15 March, CIWRO and NSSL research staff began coordinating the placement and timing of forecast domains with the OSTI WoFS Administrator and several NWS Forecast Offices. During the event, these staff monitored the progress of WoFS to ensure the timely delivery of forecast output. Several CIWRO and NSSL staff members were also embedded within a Google-based chat room between CIWRO, NSSL, and the NWS local weather forecast offices, providing analysis of the WoFS guidance and explanations on how to interpret WoFS signals in real time. Ultimately forecasters at SPC and WPC used WoFS for issuing several short-term severe weather and flash flooding products, respectively. During the wildfire outbreak, a CIWRO researcher with emergency management experience was embedded in the Norman WFO to assist with fire weather applications of WoFS, CIWRO software developers worked with NWS OSTI transition partners to configure the system and help to debug technical issues. NWS Southern Region forecasters used WoFS to provide more accurate smoke forecasts, and forecasters remarked at the ability of WoFS to assimilate ongoing fires in real-time. On 14 March, WoFS guidance helped forecasters notify a county Emergency Manager of high-wind potential with several hours' notice so that a large outdoor event could be moved indoors. On 15 March, the NWS Nashville, TN forecast office utilized WoFS rainfall and instability products and the discussion points within the NWS-to-NSSL chat room to communicate hazardous weather threats while being embedded within the Tennessee State Emergency Operation Center. Finally, SPC forecasters used WoFS guidance to extend an expiring tornado watch, since WoFS indicated a threat from upstream storms. In summary, this intellectual opportunity showed WoFS is useful for increasing forecaster confidence, and in many cases can accurately identify tornadic storms at greater than 90-minute lead times. For example, in Missouri on 14 March evening, a forecaster pointed out that WoFS identified the exact location of a tornadic storm 90 minutes in advance.

When heavy rainfall and flooding trapped a Thai boys' soccer team in a cave during the summer of 2018, Norman-based Weather Decision Technologies (WDT) was enlisted to aid in the rescue. Experts in weather risk mitigation, WDT used weather forecast software developed through CIMMS/CIWRO and licensed from OU to provide rescuers accurate rainfall predictions to plan critical mission timing. (https://www.ou.edu/otc/impact | WDSSII)

f. What is the strategy for new starts (projects, techniques, campaigns, etc.)?

Section 4.a previously described how CIWRO identifies new intellectual opportunities: professional development time for staff; DDRF proposals sponsored by indirect cost return and a VPRP cost match account; workshops designed to bring diverse communities together, especially including other partners within the NWC and our consortium partners, along with expertise we lack within CIWRO from other institutes; attendance at professional conferences to stay abreast of developing science and technologies; and development of proposals to targets of opportunity (i.e., request for proposals) from NOAA and other agencies. Funding for new starts comes from the above variety of sources. We also use Task III funding as a proving ground for new projects that can be further pursued as collaborative work with federal partners. Based on workshops and informal conversations, we develop short white papers (approximately one page) describing new ideas for which we believe further funding could jump-start new intellectual opportunities. These are supplied to our TPM and other NOAA program managers so that they are aware of these new ideas.

i. How much of the Institute's resources are reserved for new opportunities or bright ideas?

Institute resources are used for the following new opportunities and bright ideas: DDRF proposals that emphasize collaboration with our consortium partners; funding for the Pete Lamb postdoctoral fellow; workshops to bring together individuals from different groups across CIWRO, consortium and external partners, and outside expertise as appropriate; Task III proposals and response to external calls for funding; and professional development time of staff members. These activities have been described in previous sections.

In terms of resources allocated to each of these tasks, since 1 October 2021 the total funding for the DDRF proposals is $450,000; for the Pete Lamb postdoctoral fellows $472,117; for the workshops, approximately $70,000; for the Task III proposals, $14,034,915 for a maximum of 20.0% of CIWRO's budget as not all Task III proposals involve new opportunities or development of bright ideas; for Professional Development, this would be less than 10% of the CIWRO budget because but not all staff members spend their professional development time on pursuing new opportunities or developing bright ideas.

ii. Are these activities Task I, Task II, or Task III projects?

The source of funding for these activities is varied. The DDRF proposals are from sponsored research imitative (SRI) which is return from indirect costs that CIWRO receives from OU. The Pete Lamb postdoctoral fellows program and the workshops are funded by Task I funds. The writing of proposals or development of new work plans for Task III funds or response to external calls for funding are sponsored either by the VPRP cost match account from the professional development time of staff members (10% of their effort).

g. What is provided for human resources development (recruitment, rewards, training, etc.)?

For recruitment, all positions are openly advertised and competed. To this effect, all positions are open for a minimum of two weeks to ensure there is time for all interested parties to see the open positions and apply. In addition, all announcements are written to be as broad as possible (within the constraints of the needs for the position) in order to encourage as many applicants as possible to apply. Other sections below describe how compensation and financial rewards are provided to CIWRO employees.

i. How are the CI employees provided training in HR issues (e.g., benefits, retirement)?

All CI employees are provided with training in HR issues as appropriate. For example, information on benefits and retirement is communicated to all new employees through a benefits orientation event conducted by the HR department at OU. After, employees participate in annual open enrollment periods, where updates and relevant information is provided online and through benefits fairs where employees have the opportunity to visit with representatives from different companies that provide or administer benefits for the university. Retirement options are also provided to new employees and are available online. There are also options available for consultation.

ii. Do CI employees participate in general NOAA HR training when appropriate?

Yes, CI employees participate in general NOAA HR training when appropriate. Examples of training that CI employees participate in include the following: General Security Awareness Course; Department of Commerce Cybersecurity Awareness Training; Annual Records Management Training; Foreign Travel Training, and others as appropriate.

iii. How are CI employees, particularly the most junior, provided with future employment training to be successful upon leaving the CI?

Although many CIWRO employees have long careers in the organization and treat their employment as a career position, there are some employees (particularly graduate students and postdoctoral fellows) who transition to other career paths after their employment in CIWRO. CIWRO provides a variety of training opportunities to all employees regardless of whether they stay with CIWRO or choose alternate career paths (such as in the federal government).

One of the primary ways that CIWRO employees receive guidance is through mentorship opportunities. The majority of the mentorship that occurs is through more senior members of CIWRO mentoring more junior members on their specific teams. CIWRO works to ensure that junior employees are integrated into teams where there are more senior members to ensure that these mentorship opportunities are available. In addition, CIWRO has a formal mentorship program that gives CIWRO employees the opportunity to be paired with a mentor on another team if they feel that they are not adequately receiving enough mentorship on their

own team. An email to remind employees about CIWRO's mentorship program is sent to all employees, including graduate students and postdoctoral fellows, every six months.

In addition, OU has the Office of Postdoctoral Affairs (OPA) that is aimed at creating and supporting a university-wide community and culture that enriches the postdoc experience at OU. OPA helps to support postdoc onboarding and professional development and provides community and support for postdoctoral researchers and their mentors. The website of this program (https://www.ou.edu/gradcollege/population/postdoc) provides guidance for post-doc mentors in mentoring, evaluation of postdoc researchers, use of postdoc research titles, and other topics. In addition, when CIWRO scientists seek external funding, they are typically required to write a postdoc mentorship plan that defines how they will provide project-based and professional guidance to any postdocs hired to work on the project.

There are also multiple opportunities for graduate students. Within the School of Meteorology, there are mentoring ecosystems that are open to both graduate and undergraduate students. Mentoring ecosystems are a collection of 5-10 students and an advisor (e.g., faculty member, CIWRO researcher, etc.) that meet together once each semester and have individual meetings between the advisor and individual students as needed. The mentoring ecosystems are focused on specific topics such as how to get involved and succeed in undergraduate research, exploring the meteorology public sector, study abroad, exploring the meteorology private sector, building your network, delving into AI and meteorology, CVs/resumes for the job search process, social sciences and meteorology, navigating the School of Meteorology as a transfer student, and how to apply and get into graduate school.

Working with the Student Activities Center, CIWRO also sponsors a couple of events each year designed at providing guidance on topics that undergraduate, graduate students and postdoctoral fellows might find beneficial. In spring 2025, there are two events: Resumes, CVs, and the job search process; and how and where to seek employment in the atmospheric sciences. Typically, these events involve a panel of 4 to 5 members with varied backgrounds, who provide introductory remarks and then proceed to answer questions from the students and postdocs who attend the event.

Many CIWRO scientists are affiliates of the School of Meteorology or the School of Electrical and Computer Engineering at OU, and as such serve as the research advisor of graduate students. Each year the advisor and graduate student must sign a contract "Graduate Student Advisee/Advisor Expectations" that clearly define the expectations of both the advisor and student so that there is a common framework for a safe and supportive environment that promotes a successful and productive advisor/advisee relationship. In this document, it is clearly stated that the advisor's role includes "understanding and supporting the career plans (e.g., faculty, research, operational meteorology, private sector) of the advisee. This support could include taking career plans into account when selecting courses, conferences, and seminars at other institutions." It also clearly states that the advisee's role includes "sharing their vision for career paths with their advisor."

Finally, CIWRO provides opportunities for all employees to attend regional, national and/or international conferences. This allows CIWRO employees to be exposed to work going on in their discipline. Additionally, there are career development opportunities and workshops available at the annual conference of the American Geophysical Union and of the American

Meteorological Society, which many CIWRO employees attend.

OU through its Human Resources department also provides a wide range of opportunities for in-person and on-line training opportunities to equip employees with the knowledge, skills and resources necessary for career and leadership success and personal achievement (see https://hr.out.edu/Employees/Career-Development/Worskhops-Programs). As each employee is unique, employees are encouraged to collaborate with their supervisors to identify learning experiences aligned to their position, career, personal development and organizational goals. A focus on professional and personal development not only enriches individuals but also strengthens CIWRO's collective capabilities. In brief, OU offers diverse learning opportunities, expert facilities, collaborative environments and support for career advancement. Examples of courses include the following: Effective feedback, the art of balance; cultivating civility in your work environment; 5 actions to boost employee engagement; designing for the end user experience; engagement best practices; developing student employees-undergraduate and graduate; work-life survival: choosing satisfaction over balance; common meeting mistakes and how to overcome them; creating an engaging workplace; appreciative leadership; motivating others to be their best; supervisor foundations; introduction to data modeling and analysis; building a culture of continuous feedback; mental health first aid; and many others. OU also has a new leader development program described at https://hr.ou.edu/Employees/Career-Development/Learning-Development/New-Leader-Development and a program cultivating conscious leadership.

Further, OU has also partnered with LinkedIn Learning to offer more training and learning opportunities. LinkedIn Learning is a renowned leader in online training and offers a vast digital library with over 13,000 courses, spanning a wide array of subjects including business, software and created topics. This allows CIWRO employees to learn at their own schedule and pace, with expert-led instruction accessible from any device, anywhere.

h. What is the state of the financial health of the Institute?

CIWRO has received award funding through the NOAA cooperative agreement of $70,278,590 through OU Fiscal Year 2025, with a 92% expenditure rate through OU Fiscal Year 2025.

Of the $70,278,590 awarded through the cooperative agreement, 77.27% ($54,304,520) in funding was awarded on Task II awards with substantial research involvement from NOAA federal scientists, 19.97% ($14,034,909) was awarded on Task III funding for research that can be completed with minimal research involvement from NOAA federal scientists, and 2.76% ($1,939,161) was awarded on Task I for educational work, outreach, and administrative work required within the cooperative agreement. CIWRO received an additional $504,642 in Task I funding for administrative work related to supplemental awards as outlined by Congress (Inflation Reduction Act, Bipartisan Infrastructure Law, Disaster Relief Supplemental Awards related research.)

CIWRO has also received $12,672,169 in direct-to-CI awards outside of the cooperative agreement since the start of this current cooperative agreement in 2021 (OU Fiscal Year 2022), allowing for our research capabilities to be further leveraged outside of the cooperative agreement to benefit NOAA and OU. As outlined in the CIWRO proposal, OU has provided

cost match support to CIWRO and to further the OU/NOAA partnership. OU has provided $5,336,665.68 in cost match funding since the start of the current cooperative agreement. CIWRO receives funding for the CIWRO Director's salary and 75% of the CIWRO Executive director's salary annually, a minimum of $250,000 in indirect cost return from the College of Atmospheric and Geographic Sciences Dean's Office annually (average return is $380,333.33 annually), and a $750,000 annual cost match contribution from the Office of the Vice President for Research and Partnerships. NOAA also receives a lowered indirect cost rate for NOAA awards at OU; the NOAA indirect cost rate is 26% compared to the standard research indirect cost rate of 55%.

Category	CIWRO	AGS	OU
Research Scientist	$93,464	$74,670	
Research Associate	$79,998	$56,385	
Postdoctoral Fellow	$63,364	$60,988	$56,152
GRA	$31,442	$31,349	$22,560
Sr. Research Associate	$122,415	--	
Sr Research Scientist	$174.696	$106,506	
Administrative	$56,199	$62,388	

Table 4-1: Comparison of average salaries in CIWRO to College of Atmospheric and Geographic Sciences (AGS) and OU as a whole

Because the financial health of the institute is quite good, CIWRO has made extensive efforts to ensure that employees within CIWRO have equitable compensation compared to other CIWRO employees. Further, Figure 4-1 shows that compared to all other units on OU campus, CIWRO postdocs are paid the highest. Table 4-1 compares the salaries of employees in CIWRO to those of employees in the College of Atmospheric and Geographic Sciences (AGS) and OU as a whole. Both of these comparisons show that with the exception of the administrative staff, CIWRO is paying their employees at rates comparable to, or greater than, the rest of the university. However, a substantial inequity in the pay of CIWRO employees against those of federal employees with similar experience and performance attributes working alongside the CIWRO employees doing similar jobs exists. CIWRO is undertaking initiatives to try to resolve these pay inequities as outlined below.

In 2018, when the previous Cooperative Institute existed (CIMMS) existed, an initiative was undertaken to ensure that all employees within CIMMS were paid equitably compared to each other with an attempt to establish some equity with the salaries of our federal partners. A salary survey was conducted to compare the pay within CIMMS to those in other CIs, with it being established that CIMMS employees were not as well compensated as employees in other CIs even when accounting for expected differences in pay due to cost-of-living adjustments in different locations. At that time, we also attempted to make the salaries of CIMMS employees comparable to those of federal partners (i.e., if those working on similar jobs with the same background, experience and performance) but there was little comparable information available given that the majority of CIMMS employees were early in their careers and there were no early career federal scientists to compare against. At that time, the following

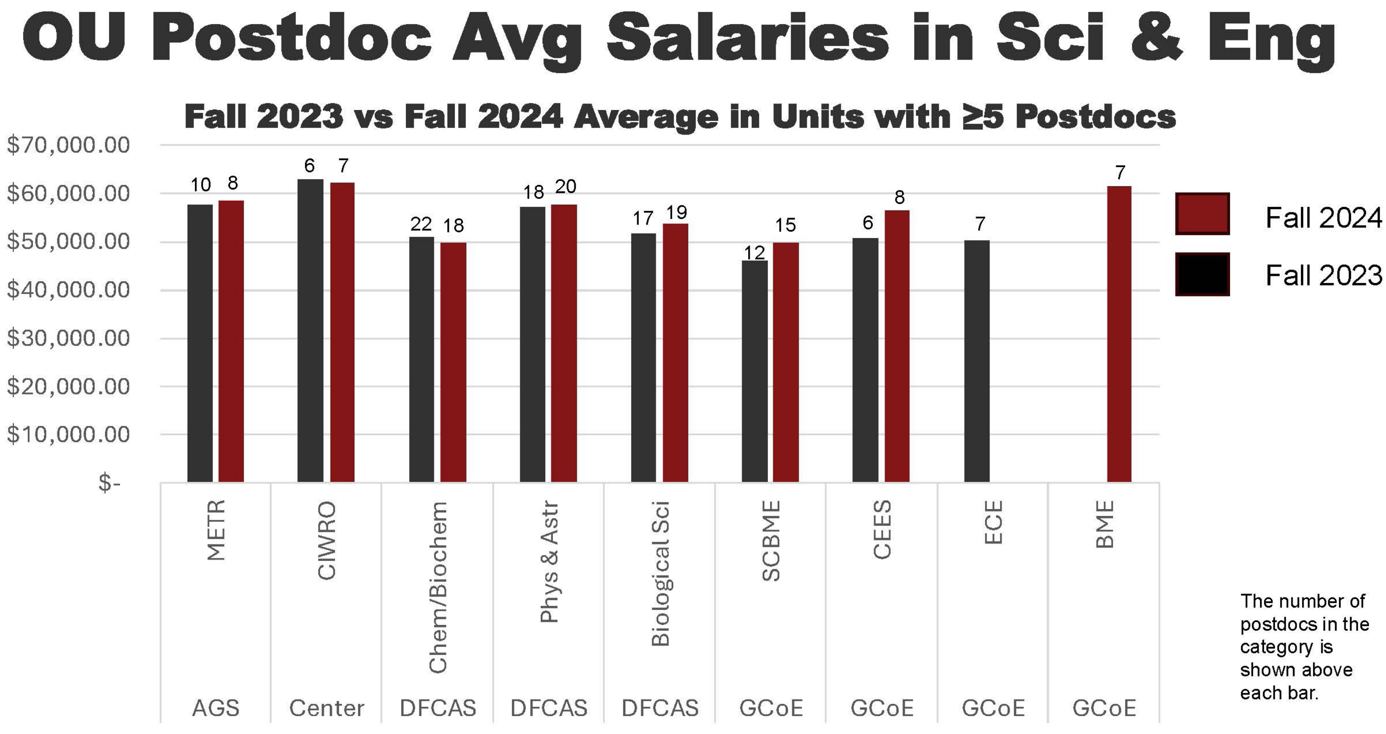


Figure 4-1: Comparison of average postdoc salaries in CIWRO compared to the rest of OU for units with greater than 5 postdocs

salary model was developed. Starting salaries for a Research Associate I (RAI) with a meteorological background was $48,000, an RAI with software development background was $55,000, and with an engineering background was $70,000. The starting salary for a Research Scientist I (RSI) with meteorological background was $65,000, with software development background was $75,000 and with an engineering background was $82,000.

Within the CIMMS (and now CIWRO) career tracks, research associates and scientists advance from category I to II to III and then to Senior (i.e., RAI, RAII, RAIII and Senior RA, and RSI, RSII, RSIII and Senior RS). The following raises were given when a research associate or scientist received a promotion: RAI to RAII ($5,000); RAII to RAIII ($6,000); RAIII to Senior RA ($7,500); RSI to RSII ($7,000); RSII to RSIII ($8,000); and RSIII to Senior RS ($10,000). Annual salary raises were designed to be equivalent to the annual salary raises of our federal partners, with the pool of the available increase allocated according to a 5/7, 7/7, 9/7 ratio and according to the employee's performance evaluation (i.e., those receiving a meets expectation rating got 5/7 raise, those exceeding expectations got a 7/7 raise, and those highly exceeding expectations got a 9/7 raise compared to the average fractional increase). Based on these assumptions and using comparison against the salaries of existing federal employees, we set salaries of all existing CIMMS staff to follow this salary model. For those joining the CI with more experience than an employee out of college, we used their background and past performance to set a salary offer—we did not and do not negotiate salary offers to ensure that we maintain internal equity among employees.

Although this model that was established ensured equity among CIMMS/CIWRO employees,

it very quickly ran into problems with a lack of equity with federal employees for several reasons. First, the federal partners started to hire early career scientists at pay rates that greatly exceeded what was being paid to the CIWRO early career scientists. Second, the majority of federal partners were more senior level scientists that received lower fractional pay increases than more junior employees because they were at the top of their pay bands. Because at that time, our major federal partner mandated that the total raise pool available to CIMMS/CIWRO employees could not be greater than what federal employees received (in proportion to the number of employees in each unit), this further constrained the pay increases of early career CIMMS/CIWRO employees. Third, when CIMMS/CIWRO employees promoted or transitioned from an RA to RS position (e.g., on receipt of Ph.D. and associated job change responsibilities), our federal partner mandated any pay increase for the promotion/job change also had to come from our available pool for salary increases. Fourth, we could not increase the starting salary of those joining CIMMS/CIWRO because this would have caused inequities within CIMMS/CIWRO with more junior scientists making more than their senior counterparts because of our inability to grant appropriate raises to our existing staff. Fifth, at that time OU limited the raises we were able to give to our employees, which were insufficient even though the raises we were able to provide were greater than the raises that state-supported employees at OU received.

Despite all these challenges, CIWRO has developed a strategy in the past year that will allow us to gradually eliminate these pay inequities. Recognizing the need to attract and maintain technical talent, OU no longer limits the raises that CIWRO employees can receive. And, the new TPM acknowledges these pay inequities exist and has encouraged us to develop a strategy to solve the problem. Further, he acknowledges that CIWRO is free to set the salaries of their own employees without federal interference. However, a strategy to solve these inequities will take time as the needed funds to increase CIWRO employee salaries to equitable levels are not currently available. The strategy to achieve equity is based on the following principles: 1) No position at CIWRO will be eliminated to increase the salary of others; 2) Only positions that are highly mission critical and which require skills that no current employees at CIWRO have will be filled; 3) When appropriate and synergistic with our existing activities, we will seek external funding so that more funds are available to support CIWRO employee salaries.

We have proceeded in three steps in our new competitive pay program.

In fall 2021, the first component of our competitive pay program brought the pay of radar engineers in CIWRO to equitable levels. CIWRO relies on engineering expertise to conduct its critical Weather Radar and Observations Research & Development mission. Currently, CIWRO engineers are embedded in and make up about 80% of the engineering workforce at NSSL, our largest federal partner. In fall 2021, CIWRO was facing significant challenges associated with recruiting, hiring, and retention of engineers, with compensation being a major factor. Exacerbating the problem was inequities within different departments at OU, especially with the OU Advanced Radar Research Center (ARRC) where there were radar engineers with similar expertise being paid significantly more than CIWRO radar engineers. Thus, a detailed study was prepared to compare the salaries of CIWRO engineers with those in the ARRC taking into account differences in equivalent years of experience and terminal degree. Based on this, a new salary model was implemented for CIWRO engineers where initial starting sala-

ries were set to $73,834 (B.S. degree), $83,678 (M.S. degree) or $87,684 (Ph.D. degree) with promotion raises of $10,000 (I to II), $12,000 (II to III) and $14,000 (III to Senior) as engineers develop their careers. The actual salaries of all CIWRO engineers were then set according to the CIWRO salary model where annual raises were historically determined based on the employee's historical performance review ratings.

The second program, implemented in spring 2022, raised the salaries of those in CIWRO working on software development. CIWRO classifies employees as developers if the majority of their job duties involve the development of research software in support of the CIWRO mission. While many researchers in CIWRO write software in support of their own research, CIWRO developers are unique in that they write software that supports the research of others. This research software typically runs in real time and is directly transitioned to or implemented in systems that support the research mission of CIWRO and/or the research and operational missions of NOAA. Employees in this category also have formal college-level training or equivalent demonstrated experience using computer-science concepts. At the time the CIWRO software compensation program was created, CIWRO was facing significant challenges associated with the recruitment, hiring, and retention of developers, with employees leaving for higher-paid positions and citing inadequate compensation as one of the main reasons for leaving, and candidates declining job offers due to an inadequate pay package. At the time, we were worried about the ability to fulfill goals of our funded projects given the difficulty in attracting and retaining employees. Thus, we updated the salary models of CIWRO developers in three different sub-categories (A computer programmers; B software developers; C computer and information research scientists) that were based on three of ten different classifications for software developers found in the "*Computer and Information Technology Occupations*" section of the "*Occupational Outlook Handbook*" (https://www.bls.gov/ooh/computer-and-information-technology/home.htm). For each of these classifications, the USBLS provides pay statistics (under the "Pay" tab), including median annual wages and annual wages corresponding to the 10th and 90th percentiles with the statistics covering all types of employers across the US and employees with all levels of experience. Updated initial salaries for CIWRO developers in each sub-category were set using the 10th percentile wages listed for each relevant USBLS classification. The actual salaries of the CIWRO software developers were then determined by adding promotion raises according to the level of each employee, and performance raises based on their previous performance evaluations. Since implementing this program, no software developers have left CIWRO.

The final step of the strategy in ensuring pay equity is the development of the CIWRO Competitive Pay Program (CPP) which is a strategy to increase the salaries of those classified as meteorologists, which are the majority of our staff members. This is a multi-year effort to gradually increase the salaries of meteorologists to eventually reach a pay scale that is more competitive with federal salaries. The newly developed pay model attempts to solve the current problems in the CIWRO compensation structure:

1) Starting salaries for meteorologists are not competitive with those from the private sector or federal government with competing offers typically $10K to $15K higher; thus, starting salaries are increased by $12K in the new model.
2) Salary growth in the first half of a meteorologist's career has been slow because raises are based on percentage increases; thus, the CPP gives higher relative raises in earlier

parts of a person's career, resulting in stepper increases in pay as compared to the current model.

3) In the current model, when people promote, they do not receive a merit raise; in the CPP merit raises are given simultaneously with promotions.
4) The current salary model is static and has not kept up with inflation; the CPP has an inherent baseline that can be adjusted to keep pace with inflation.

Trends in federal pay were used to develop the salary model in the CPP. In particular, the CPP provides a similar growth rate to the federal merit pay increases and allows for the variability imposed by inflation. Nevertheless, there is not an exact one-to-one correspondence in salaries of CIWRO and federal employees as there are some inherent differences in job duties and responsibilities. To develop the CPP, the history of employment, promotions, and performance evaluations of every employee was reviewed in order to determine their target salary so that the CPP would be internally fair and equitable.

However, the existence of the salary model does not permit its immediate implementation because there is insufficient funding available to cover the pay increases. But a strategy to achieve equity and the new salary model has been established. Each year a "percent milepost" dictated by the available funding is established to determine how much progress from the existing salary model to the CPP equitable model can be made. In 2024, a 25% milepost was established. Requests were made to the federal partners to meet the milepost, which was reached on some projects but not available for other projects. For those projects where funding was not available (e.g., insufficient Task II or Task III funding, or on direct-to-CI funding through external grants), funding from the OU VPRP cost match account was used to pay for the salary increases. This process will be repeated each year until salary equity is achieved. It is not known how long it will take to reach the new model as it depends on the availability of funding and how large the individual adjustments need to be in the years that milepost raises are given. It is also noted that CIWRO meteorologists do not necessarily get identical pay raises in each milepost adjustment as it depends on how far the current pay of the employee is from their targeted pay.

i. How does the Institute intend to work towards accomplishing its financial goals?

The CIWRO Executive Director and financial staff oversee all payroll charges, purchases, travel expenses, and subrecipient invoices for accuracy, applicability to the project, and allowance under federal uniform guidance and award terms and conditions on a daily basis. All expenses are reviewed by the CIWRO financial team, then the OU Office of Research Financial Services, and the Principal Investigator of the project for accuracy at the time of the charge, and then on a monthly basis through statement of accounts sent out to PIs and expenditure certifications that must be signed and returned to the CIWRO financial team for record keeping. Labor certifications undergo an additional approval on a semester basis for accuracy by the PI and the CIWRO financial team. The CIWRO Director receives monthly statement of accounts on projects under the cooperative agreement for review, in coordination and consultation with identified project leads and the CIWRO Executive Director.

CIWRO leadership coordinates with NOAA leadership on an annual basis to understand the research priorities from the NOAA research lab or line office and, with that information in

mind, CIWRO proposes an annual budget to complete the research goals outlined by NOAA, including salary+fringe, domestic and international travel, publication costs, university supplies and equipment, tuition remission for graduate students, indirect costs (at the lower negotiated NOAA rate of 26%), and Task I rates, as set by NOAA CIAO office annually. NOAA takes this information into consideration during their budget planning and then sends their annual funding release on the associated Task I/II/III projects based on funding availability and research priorities. CIWRO leadership and division leads review monthly statements to ensure spending rates are in alignment with proposed spending and research tasks.

i. Are there any issues in interacting with NOAA that require attention?

While interactions between NOAA and CIWRO are generally positive, there are areas that could be strengthened. For instance, over the years, the relationship between NSSL federal employees and CI staff has evolved, with a noticeable decline in scientific planning discussions. Previously, CI employees were regularly consulted on research directions, but these decisions are now increasingly made without their input. This shift is concerning, as CIWRO staff are often the most actively engaged in the research. Incorporating their expertise and perspectives would enhance the scientific process and could lead to more informed decision-making. An example of this is the newly formed Science Council at NSSL, which is composed of federal employees only.

NOAA partners impose physical and logistical access limitations on foreign nationals, creating challenges for collaboration and execution of project tasks. Besides hindering the integration of expertise, this impacts our ability to meet project goals. Security issues with the Horus radar has also caused the ARRC to institute certain policies regarding foreign national students, which have had a negative impact on our ability to meet research objectives. We are getting support from OU's Office of Export Controls to balance security and our educational mission to hopefully alleviate this concern.

There is some difficulty in transitioning the results of research into operational products. In particular, NWS has not been able to transition WoFS. This has created a backlog of planned transitions. At present, there is no methodology for how these algorithms are supposed to be transitioned.

Frequent changes to the Rapid Refresh Forecast System and other next-generation NOAA modeling systems have made it challenging to develop, evaluate and deploy new forecast guidance based on these systems.

Effective communication occurs often between senior OAR leadership and CIWRO leadership, but less so with senior NWS leadership despite CIWRO's research having a major impact on the development of Operational and Training Products and delivery of training to NWS forecasters. Consequently, some CIWRO employees have indicated that NWS senior leadership appears to ignore CIWRO and the contributions it brings. It is sometimes evident that the NWS leadership mainly classifies CIWRO as another "contractor", or as a "non-labor" expense subject to potential first elimination with tightening budgets. Senior NWS leadership would do

well to utilize the significant institutional NWS knowledge and expertise possessed by CIWRO when engaged in strategic planning activities and to acknowledge the significant contributions of CIWRO to the NWS mission, such as the inability of NWS staff to meet their own internal and critical training requirements without the invaluable contributions of CIWRO staff. Working with the NWS Radar Operations Center as part of the Tech Transfer has also impaired our productivity due to unexpected reductions in funding and changes to research objectives.

Although the NOAA leadership well understands the necessary separation of federal staff from employment-related matters of CIWRO employees, there are some federal staff members who inappropriately try to get involved in such matters. This can lead to a lot of confusion on the part of our staff members who sometimes believe they have received approval for activities that cannot be granted by federal employees. It would be much better if federal employees could refer CIWRO employees to their CIWRO leadership team if they are approached about personnel issues that should be addressed by us.

j. Are there any issues in interacting with the university that require attention?

One of the primary challenges CIWRO faces with OU is the increasing administrative burden placed on both research scientists and administrative staff over the past five years. CIWRO's limited administrative capacity struggles to keep up with these growing demands, diverting scientists' time away from their research. While individual administrative tasks may seem minor, their cumulative effect creates a significant strain, leaving staff in a constant reactive mode that hampers strategic planning and research efforts. Notably, CIWRO manages over 250 sponsored projects with only five staff members—far fewer than other campus units with smaller research portfolios.

Several recent procedural changes have exacerbated this burden. OU's transition to biweekly payroll, for instance, requires additional error-checking, adding nearly two extra weeks of work annually for CIWRO's HR specialist. The implementation of this change also led to financial strain for newer, lower-paid employees due to a two-week payroll delay.

Other administrative hurdles include prolonged background check processes, increased complexity in approving foreign national visits, and extensive documentation requirements for both domestic and international travel. The travel reimbursement process remains cumbersome, with necessary expenses—such as motion sickness medication for field campaigns—often disallowed despite grant approval. The Concur system frequently malfunctions, making airfare purchases inefficient, while strict lodging policies can force employees into inconvenient or potentially unsafe accommodations.

Additional challenges include:

- Increased scrutiny on job titles, potentially complicating field research roles for students.
- Onerous remote work approval and certification requirements.
- Repeated re-submissions for payroll and cost transfers due to heightened scrutiny.
- Lengthy delays in computer purchasing for non-standard equipment.

A broader concern is the lack of input from research units on policy changes, which are often implemented unilaterally. A recent example is the change in PTO payout policies, which conflicted with CIWRO's established funding constraints. Additionally, slow contract negotiations with private industry and non-standard funding agencies have led to missed research opportunities due to prolonged response times from OU's legal team. These administrative challenges collectively hinder CIWRO's efficiency, limiting its ability to focus on its core research mission. Addressing them would significantly enhance both productivity and morale.

k. What progress was made towards the performance measures the CI uses to gauge, quantify, and/or evaluate progress on both individual projects and its overall performance?

Section 1.c.1 listed the criteria that the CIs agreed upon in 2018 to measure the progress in accomplishing the goals of CIs. In this section, those metrics that apply to CIWRO are quantified to the best extent possible.

Science Dissemination:

Number of papers in peer-reviewed journals: Over the lifetime of CIMMS/CIWRO (since 1978), 1,705 papers have been published in the refereed literature. For the time period of CIWRO, there have been 353 publications in the refereed literature. When evaluating this number, it should be noted that as the focus of many CIWRO employees on development of training materials or the transition of research into operational products, there will be a lower rate of papers per employee compared to CIs where the only focus is on publishing research results. This is also evidenced by the fact that CIWRO has 60 Research Associates and 40 Research Scientists, where the Research Associates are more responsible for support of research, transition of research to operations, and development of training materials rather than leading science research projects.

Number of non-referred reference documents (e.g., NOAA reports) *and conference presentations generated per year*: Although ideally these documents should have a DOI to be easily traceable, this is frequently not the case as many presentations at annual meetings of the American Meteorological Society or American Geophysical Union, topical meetings, and workshops are not assigned a DOI. Since the formation of CIWRO, CIWRO researchers have presented 837 conference presentations which represents an average of approximately 240 presentations per year. The impact of these presentations is quite large as at the recent American Meteorological Society meeting alone there were over 100 presentations from CIWRO researchers. In addition, CIWRO researchers have completed 10 technical reports during the time period CIWRO existed.

Research Impact:

Number of products transitioned into operations: This is the number of techniques, algorithms, instruments or products transitioned into operation by NOAA, another government agency or private company, and which are currently operational or ready for operational use pending approval from NOAA or another agency. The quantitative measure of the number

of products transferred is 55. However, because of the variable effort required to develop products (e.g., 1 major product can require more work than 20 minor products) and possible ambiguities on how the products are defined, it is important to examine what some of these tech transfers were. Details on the exact tech transfers completed are included in a Appendix D.

In addition to tech transfers, CIWRO has other efforts that should be considered when assessing the impact of the CIWRO research. For example, 58 different datasets have been generated by CIWRO researchers since 1 October 2021. Over 17 Terabytes of data have been quality controlled including more than 5,000 variables per day being quality controlled by the ARM Data Quality Office. Further, 173 field interviews have been conducted by the Behavioral Insights Unit at CIWRO. CIWRO teams combined have conducted 75 testbed evaluations. CIWRO has also made important contributions to software development and updates, with 73 changes to vMRMS, and publication of over 100 software algorithms. For the Advanced Technology Demonstrator over 1.3M lines of software have been developed, with over 900 pull requests and 3,000 commits during the same time period. There have also been over 4.3 million reports to the mPING system since 1 October 2021. Four instruments have been developed.

Number of refereed papers based on data or models that were created with support from the CI by authors not belonging to or related to the CI: As many of CIWRO's products and tools are distributed by NOAA (e.g., MRMS product, data obtained during field campaigns) and are publicly available, there is no easy way to ensure that we are able to track and include all such refereed papers. Nevertheless, an attempt was made to determine a lower bound for this number. For example, a search on journals of the American Meteorological Society shows that there are 540 different articles where MRMS occurs. A similar search for WoFS yields 266 papers. Although some of these papers were no doubt written by CIWRO authors, this clearly shows the great impact of the data and models being developed by CIWRO.

Funding leveraging: The amount of funding from NOAA and other sources that supplements CI funding. Since the formation of CIWRO, 49 external non-Task-III proposals have been funded for a total of $28,437,590 from NOAA outside of the Cooperative Agreement and $14,523,395 from non-NOAA sources.

Number of PhD and MS degrees awarded to students supported by the CI: Although CIWRO does not maintain information on the number of degrees awarded to students per year, we do have information on the number of students supported by CIWRO per year. Currently there are 30 graduate students and 68 undergraduate students supported by CIWRO. Over the lifetime of CIWRO (since 1 Oct. 2021), there have been 47 graduate students and 130 undergraduate students supported by CIWRO.

Number of CI-supported students/postdocs/research scientists/research associates who have obtained employment in positions related to the fulfillment of NOAA's objectives: The CIWRO HR Director conducts an exit interview with all CIWRO employees who depart. Since 1 Oct. 2021, 23 Research Associates have left CIWRO: 2 left for personal reasons, 5 retired, 5 found a federal job, and 11 found a new non-federal job. For the 20 Research Scientists that voluntarily left CIWRO, 1 left for personal reasons, 1 retired, 1 returned to school, 7 found a federal job, and 10 left for a new non-federal job. Of the 21 Associates and Scientists who left for non-federal

jobs, 17 found jobs that had some relation to the fulfillment of NOAA objectives, with many of those being in private industry or at other universities. A total of 32 graduate students supported by CIWRO have passed their M.S. or Ph.D. defense since 1 October 2021. Of these 32 students, all but 2 are either pursuing their Ph.D. degree (i.e., those who graduated with a M.S. degree), or are employed by either private industry or another university, all doing work in support of NOAA's objectives.

Course	People	Course Duration	Total Time	Comments
Active Learning for IDSS course (published Jan. 2022)	597	30 min	300 h	Hundreds more viewed some portion of course but have not completed final exam
21 Foundations webinars	630	4 h	2,520 h	Each webinar is 4 h
In-person component of Foundation course	1,018	Varying duration	8,780	14 different courses attended by different number of people and with different durations (25% of NWS workforce have attended)
Field Operations Managem't	60 students	6 classes of 1.75 h each; 3 classes of 1.5 h	1,363 h	Six 1.75 h classes attended by 60 students; Three 1.5 h classes attended by 7, 25 and 30 students
Strengths training delivered to individual WFO Office	14	1 h	14 h	
Boot Camp courses (deployment and tropical boot camp)	49	Varying	1,544 h	Flipped classroom concept where students spend time practicing skills instead of listening to presenter (varying numbers of students attended different classes)
TOTAL			**14,520 h**	**Combined efforts of NWSTC training**

Table 4.2: Time training produced by NWSTC was consumed.

Amount of time CI-produced training is consumed both in person and on-line: There are three major groups in CIWRO that produce training, those in WDTD, NWSTC, and SPC. The time is calculated by multiplying the duration of each course by the number of attendees at that course. Estimates for the amount of time training produced at these three locations is provided separately.Since October of 2021, CIWRO employees at NWSTC have worked on several different projects and efforts in conjunction with Federal employees. It is difficult to separate the involvement of CI and federal employees in producing material in the form of websites, presen-

tations, one-pagers, course resources into consumed training time. Thus, the calculation for the time CI-produced training is consumed only includes the time for which a CIWRO employee was actually delivering content as the main instructor or point of contact for a course or session, and does not include the time spent by CI employees preparing courses, developing material, or altering course content based on evaluations. Table 4-2 shows how the time CI-produced training produced by NWSTC was consumed is calculated as 14,520 h.

Course	People	Course Duration	Total Time	Comments
Radar and applications course	455	100 h	45,500 h	
WOC-winter course	500	30 h	15,000 h	
WOC-flash flood	3,200	19 h	60,800 h	
WOC-severe course	326	26 h	8,476 h	
WOC-human factors	617	9 h	5,553 h	
Storm of month webinars	1,300	1 h	1,300 h	
R2O and O2R webinars	475	1 h	2,375 h	175 live plus 300 views of recordings for 5 webinars of 1 h each
AWIPS build training	400	10 min	67 h	
AWIPS fundamentals	400	15 h	6,000 h	
CLAS for training activities	2,625	3 h	7,875 h	
Post-storm damage survey training	5,700	25 min	2,375 h	
Probabilistic IDSS training	1,764	6 h	10,584 h	
TOTAL			165,905 h	

Table 4-3 Time training produced by WDTD was consumed.

Similarly, an estimate can be made of the amount of time CI-produced training is consumed from the work done by CIWRO employees at WDTD based on the professional training activities that are described in Section 3.b.2. Table 4.3 shows how this estimate is derived.

These totals combined to a total of 165,905 h for on-line and in-person training from WDTD-activities. But there are additional trainings for which it is not possible to provide as good of an estimate. There are 5,700 completions of AWIPS cloud archive training, but this training is more informal and is not tracked in the same way as the others. Similarly, training on the hazard services warning generation tool is not formally tracked even though the job sheets that are part of this training are very critical to the production of warnings by the NWS, so it is not possible to give a quantitative estimate of the time consumed.

CIWRO/SPC researchers also provided presentations during regularly scheduled semi-annual training periods for SPC forecasters. The purpose is to provide updates on recent enhance-

ments to forecast technology stemming from CIWRO research as well as the latest understanding of storm dynamics that could impact forecast capabilities. Table 4-4 provides a list of presentations that were provided by CIWRO staff to SPC forecasters since Fall of 2021. Each presentation was given to five or six forecasters and repeated four times over a course of four weeks in order to accommodate all 22 SPC forecasters. Thus, the total hours of training of 28.66 is multiplied by 5.5, the average number of forecasters per session, to get a total of 158 hours of CI-produced training that is consumed by SPC forecasters.

Session	**Course**	**Course Duration [min]**	**Total Time [hr]**
Fall 2021	Satellite Update & Survey	15	1
Fall 2022	Significant-severe Environments	30	2
	Dual-pol Applications for Winter Weather	20	1.33
	Cold-season CAM Biases	20	1.33
Winter 2023	Watch Guidance	15	1
	Conditional Intensity Update	60	4
Fall 2023	Conditional Intensity Forecasting	30	2
	GEFS Calibrated Guidance Products	30	2
	ECAPE	30	2
	LightningCast Testbed	15	1
Winter 2024	Medium-range Guidance and Outlooks	60	4
	AI/ML Projects/Products at SPC	30	2
Winter 2025	Updates to IMPACTS and Results from Historical Cases	30	2
	Dual-pol Radar Products	15	1
	Hail Forecasting	30	2
	TOTAL		28.66

Table 4-4: Time training produced by SPC was consumed by a single forecaster. In all, 22 forecasters received this training.

Thus, the total of 180,454 h (equivalent to 7,519 days or 20.6 years) represents a lower bound for the amount of training produced by CIWRO that has been consumed since 1 Oct. 2021. Some trainings (i.e., hazard services warning generation tools, AWIPS cloud archive training) are not easily tracked in terms of time spent by trainees due to the design and delivery methods such as "job sheets" for on-the-job training through the NOAA Virtual Lab (VLab) system and one-on-one consultations. This is not to say the trainings are unimportant; to the contrary, they are among the most critical trainings produced. Finally, CIWRO's work enables local science and operations officers within the NWS to create and deliver their own weather event simulations to their own staff. Again, this is critically important training but not possible to be traced uniformly.

APPENDIX A: REFERENCES

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APPENDIX B: ACRONYMS

Acronym	Definition
2D-S	Two-Dimensional Stereo
2DVD	2D Video Disdrometer
3DVAR	Three-Dimensional Variational data assimilation
20CR	20th Century Reanalysis
20CRv3	20th Century Reanalysis Version 3
ABI	Advanced Baseline Imager
ABL	Atmospheric Boundary Layer
ACARS	Aircraft Communications Addressing and Reporting System
ACC	Anomaly Correlation Coefficient
ACT	Arrays in Commercial Timescales
ACT	Atmospheric Community Toolkit
ADE	AWIPS-2 Development Environment
ADQO	Air Data Quality Office
AERI	Atmospheric Emitted Radiance Interferometer
AET	Analytics and Enterprise Team
AGL	Above Ground Level
AGS	College of Atmospheric and Geographic Sciences
AI	Artificial Intelligence
AI4WP	NOAA's Artificial Intelligence for Weather Prediction
AI/AN	American Indians/Alaska Natives
AMF	ARM Mobile Facility
AMS	American Meteorological Society
AOD	Aerosol Optical Depth
ARM	Atmospheric Radiation Measurement
ARRC	Atmospheric Radar Research Center
ARL	Air Resources Laboratory
ART	Advanced Radar Techniques
ASCE	American Association of Civil Engineers
ASMD	Atmospheric Sciences Modeling Division
ASOS	Automated Surface/Weather Observing System
ATD	Advanced Technology Demonstrator
ATDD	Atmospheric Turbulence and Diffusion Division
AWAKEN	American Wake Experiment

AWC	Aviation Weather Center
AWIPS	Advanced Weather Integrated Processing System
AWS	Amazon Web Services
AWT	Aviation Weather Testbed
BAMEX	Bow Echo and Mesoscale Convective Vortex Experiment
BEC	Background error co-variances
BIA	Bureau of Indian Affairs
BIU	Behavioral Insights Unit
BL	Boundary Layer
BLPT	Boundary Layer Processes Team
BVLOS	Beyond Visual Line of Sight
CA	Cooperative Agreement
CAESAR	Cold-Air Outbreak Experiment in the Sub-Artctic Region
CAGS	College of Atmospheric and Geographic Sciences
CAM	Convection Allowing Model
CAO	Cold Air Outbreak
CAPE	Convective Available Potential Energy
CAPE-k	Cold-Air Outbreak Experiment at kennaook
CAPS	Center for Analysis and Prediction of Storms
CASS	Center for Autonomous Sensing and Sampling
Cb-WoFS	Cloud-based WoFS
CDR	Circular Depolarization Ratio
CEM	Computational Electromagnetic Modeling
CG	Cloud-to-ground
CHEESEHEAD	Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors
CI	Cooperative Institute
CIMAS	Cooperative Institute for Marine and Atmospheric Studies
CIMMS	Cooperative Institute for Mesoscale Meteorological Studies
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CIRA	Cooperative Institute for Research in the Atmosphere
CIRES	Cooperative Institute for Research in Environmental Sciences
CIWRO/CISHIWRO	Cooperative Institute for Severe and High-Impact Weather Research and Operations
CLAMPS	Collaborative Lower Atmospheric Mobile Profiling System
CLAS	Cloud Automated Schedular
CLC	Commerce Learning Center

CLEAN-AP™	Clutter Environment Analysis using Adaptive Processing
CM1	Cloud Model 1
COMBLE	Cold-Air Outbreaks in the Marine Boundary Layer Experiment
COMMAS	Collaborative Model for Multiscale Atmospheric Simulation
CONOPS	Concept of Operations
CONUS	Contiguous United States
CoP	Community of Practice
CPT	Cloud Physics Team
CPP	Competitive Pay Program
CRCM	Center for Risk and Crisis Management
CRS	Congressional Research Services
CSAPR2	C-Band Scanning ARM Precipitation Radar
CSI	Critical Success Index
C-SIGs	Convective SIGMETs
CSTAR	Collaborative Science, Technology and Applied Research
CUBIC	The Coastal Urban Boundary-Layer Interactions with Convection
CVP	Columnar Vertical Profiles
CWA	County Warning Area
D & I	Diversity and Inclusion
DA	Data Assimilation
DARPA	Defense Advanced Research Projects Agency
DART	Duplex Army Radio/Radar Targeting
DAS	Dry Aggregated Snow
DAT	Damage Assessment Toolkit
DC3	Deep Convective Clouds and Chemistry
DDRF	Directors Discretionary Research Funds
DDZ	Downshear deacceleration zone
DGES	Department of Geography and Environmental Sustainability
DGL	Dendritic growth layer
DLA	Diabatic Lagrangian analyses
Dm	Mean volume diameter
DoE	Department of Energy
DOE ARM	The Department of Energy Atmospheric Radiation Measurement
DOHs	Development and Operations Hydrologists
DOT	Department of Transportation
DPT	Differential phase upon transmission

DQO	Data Quality Office
DRARSR	Doppler Radar and Remote Sensing Research
DSP	Digital Screening Processing
ECMWF	European Centre for Medium-Range Weather Forecasts
EFM	Electric Field Meter
EF-Scale	Enhanced Fujita Scale
EFP	Experimental Forecast Program
EIL	Effective Inflow Layer
EM	Emergency Manager
EMC	Environmental Modeling Center
EnKF	Ensemble Kalman Filter
ENSO	El-Nino Southern Oscillation
EnSRF	Ensemble Square Root Filter
EnVar	Ensemble Variational data assimilation
EOL	Earth Observing Laboratory
EPIC	Earth Prediction Innovation Center
EPS	Ensemble Prediction System
ERA5	ECMWF Reanalysis
ERSSTv5	ECMWF Reanalysis Sea Surface Temperature (SST) version 5
ESCAPE	the Experiment of Sea breeze Convection, Aerosols, Precipitation and the Environment
ESLC	Elevation sidelobe contamination
ESRL	Earth Systems Research Laboratory
EWP	Experimental Warning Program
F & A	Facilities and Administrative
FAA	Federal Aviation Administration
FAC	Fundamentals of AWIPS Course
FACETs	Forecasting of A Continuum of Environmental Threats
FAR	False Alarm Ratio
FASST	Forecast Applications and Social Science Team
FBIAS	Frequency Bias
FDTD	Forecast Decision Training Division
FED	Lightning Flash Extent
FEMA	Federal Emergency Management Agency
FFaIR	Flash Flood and Intense Rainfall
FFSI	Flash Flood Severity Index
FLASH	Flooded Locations and Simulated Hydrographs

FlexDAR	Flexible Distributed Array Radar
FRANA	Freezing Rain Accumulation National Analysis
FRDD	Forecast Research and Development Division
FRP	Fire Radiative Power
FSS	Fractions Skill Score
FDTD	Forecast Decision Training Division
FV3	Finite Volume Cubed-Sphere Dynamical Core
FYRE	Four-Year Research Engagement
GCMs	General Circulation Models
GDP	Gross Domestic Product
GEFS	Global Ensemble Forecast System
GEO-XO	Geostationary and Extended Orbit
GFDL	Geophysical Fluid Dynamics Laboratory
GFE	Graphical Forecast Editor
GFS	Global Forecast System
GLM	Geostationary Lightning Mapper
GMLE	Generalized Multi-Lag Estimators
GPM DPR	Global Precipitation Measurement Dual-Frequency Precipitation Radar
GOES-R	Geostationary Operational Environmental Satellite
GRA	Graduate Research Assistant
GREMLIN	GOES Radar Estimation via Machine Learning to Inform NWP
GSL	Global Systems Laboratory
HACU	Hispanic Association of Colleges and Universities
HAFS	Hurricane Analysis and Forecast System
HAIC/HIWC	the High-Altitude Ice Crystal/High Ice Water Content
HBCT	Height Below Cloud Top
HCA	Hydrometeor Classification Algorithm
HCC	Hybrid Correlation Coefficient
HIS	Horizontal Shear Instability
HIWC	High-Ice Water Content
HIWRAP	High Altitude Imaging Wind and Rain Airborne Profiler
HPC	High Performance Computing
HREF	High Resolution Ensemble Forecast System
HREFCT	High Resolution Ensemble Forecast System Calibrated Thunder
HRRR	High-Resolution Rapid Refresh
HRRRTLE	HRRR Time Lagged Ensemble

HMT	Hydrometeorological Testbed
HMT-Hydro	HMT MRMS Hydro experiment
HS	Hazard Service
HSE	Hybrid Scan Estimators
HTB	Heated Tipping Bucket
HUJ	The Hebrew University of Jerusalem
HWRF	Hurricane Weather Research and Forecast Model
HWT	Hazardous Weather Testbed
HWT-SFE	Hazardous Weather Testbed-Spring Forecast Experiment
HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory
IBW	Impact-based warnings
IDRES	Integration of Dynamic Radar Elevation Scans
IDSS	Impact-based decision support services
IF	Intermediate Frequency
IGVC	Intelligent Ground Vehicle Competiton
IPPRA	Institute for Public Policy Research and Analysis
IMPACTS	Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Storms
IDP	Integrated Dissemination Platform
IDSS	Impact-based Decision Support System-II
IOPs	Intensive Operation Periods
IQ	Inphase and Quadrature
IRB	Institutional Review Board
IST	Integrated Sensing Team
IWC	Ice Water Content
IWT	Integrated Warning Team
JEDI	Joint Effort for Data assimilation Integration
KAEFS	Kessler Atmospheric and Ecological Field Station
KDP	Specific Differential Phase
LAFE	Land Atmosphere Feedback Experiment
LDR	Linear Depolarization Ratio
LEE	Lake Effect Electrification
LES	Lake Effect Snow
LETKF	Local Ensemble Transform Kalman Filter
LIFT	Low-level Internal Flows in Tornadoes
LLMs	Large Language Models
LLSD	Linear Least Squares Derivatives

LMA	Lightning Mapping Arrays
LNA	Low Noise Amplifier
LSRs	Local Storm Reports
LWC	Liquid Water Content
MAP	Multi-scale data Assimilation and Predictability
MARCUS	Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean
MCIT	Multi-Cell Identification and Tracking
MCMC	Markov Chain Monte Carlo
MC3E	Mid-Latitude Continental Convective Clouds Experiment
MCS	Mesoscale Convective Systems
MDA	Multiscale Data Assimilation
MDL	Meteorological Development Laboratory
MESH	Maximum Estimated Size of Hail
MET	Model Evaluation Tools
METexpress	Model Evaluation Tools express
METplus	Model Evaluation Tools plus
METviewer	Model Evaluation Tools viewer
MW	Midwest
MJO	Madden-Julian Oscillation
ML	Machine Learning
ML	Melting Layer
MLDA	Melting Layer Detection Algorithm
MPAR	Multifunction Phased Array Radar
MPAS	Model for Prediction Across Scales-Atmosphere
MPE	Multi-sensor Precipitation Estimate
MPEX	Mesoscale Predictability Experiment
mPING	Meteorological Phenomena Identification Near the Ground
MRB	Mississippi River Basin
MRMS	Multi-Radar Multi-Sensor
MRR	Micro-Rain Radar
MRV	Mid-altitude rotational velocity
MSI	Minority Serving Institution
M-SISNet	Meso-Scale Integrated Socio-Geographic Network
MSQPE	Multi-Sensor Quantitative Precipitation Estimates
MWR	Microwave Radiometers
MYRORSS	Multi-Year Reanalysis of Remotely Sensed Storms

NA	North Atlantic
NASA	National Aeronautics and Space Administration
NASH	North Atlantic Subtropical High
NBC	National Broadcasting System
NCAR	National Center for Atmospheric Research
NCAS-M-II	NOAA Center for Atmospheric Sciences and Meteorology II
NCEI	National Center for Environmental Information
NCEP	National Center for Environmental Prediction
NCO	NCEP Central Operations
NDSEV	Number of days with Severe weather Environments
NetCDF	Network Common Data Format
NEXRAD	Next Generation Radar
NextGen	Next Generation
NGFS	Next Generation Fire System
NHC	National Hurricane Center
NIDIS	National Integrated Drought Information System
NMDA	New Mesocyclone Detection Algorithm
NOAA	National Oceanic and Atmospheric Administration
NOXP	NOAA dual-polarized X-band
NRC	National Research Council
NSF	National Science Foundation
NSF/AI2ES	National Science Foundation Artificial Intelligence for Environmental Sciences
NSSL	National Severe Storms Laboratory
Nt	Total number concentration
NTDA	New Tornado Detection Algorithm
NWC	National Weather Center
NWF	National Weather Festival
NWI	National Wind Institute
NWP	Numerical Weather Prediction
NWRT	National Weather Radar Testbed
NWRT/ATD	National Weather Radar Testbed Advanced Technology Demonstrator
NWRT/PAR	National Weather Radar Testbed Phased-Array Radar
NWS	National Weather Service
NWSFO	Norman NWS Forecast Office
NWSTC	National Weather Service Training Center
O2R	Operations-to-Research

OAP	Optical Array Probe
OAR	Oceanic and Atmospheric Research
OCLO	Office of the Chief Learning Officer
OCS	Oklahoma Climatological Survey
OGAT	One Generator at Time
OKAGE	Oklahoma Alliance for Graduate Education
OKLMA	Oklahoma Lightning Map Arrays
OMB	Office of Management and Budget
OPG	Operations Proving Ground
OPT	Observations and Processes Team
ORACLES	Observations of Aerosols Above Clouds and their Interactions
ORPG	Open systems Radar Product Generator
OTB	Operations Training Branch
OTC	Office of Technology and Commercialization
OU	The University of Oklahoma
PaaS	Platform-as-a-Service
P3	Predicted Particle Properties
PACRAIN	Pacific Rain Gauge Network
PAMST	Phased-Array Meteorological Studies Team
PAR	Phased-Array Radars
PARR	Public Access to Research Records
PARISE	Phased Array Innovative Sensing Experiment
PBS	Public Broadcasting System
pCVP	Path Columnar Vertical Profiles
PDF	Probability Density Function
PECAN	Plains Elevated Convection at Night
PERiLS	Propagation Evolution and Rotation in Linear Storms
PHI	Probabilistic Hazard Information
PI	Principal Investigator
POVP	Process-oriented Vertical Profile
PPH	Practically Perfect Hindcasts
PPI	Plan position indicator
PRES^{2}iP	Prediction of Rainfall Extremes at S2S Periods
PRF	Pulse Repetition Frequency
PRISM	Parameter-elevation Regressions on Independent Slopes Model
PRODIGEE-US	Progressive research and optimization of a durable and independent generation of uncrewed aircraft systems

PRO-FLASH	Probabilistic-Flooded Locations and Simulated Hydrographs Project
PRT	Pulse Repetition Time
PSD	Particle size distribution
PSU	Pennsylvania State University
PWV	Precipitable Water Vapor
QBO	quasi-biennial oscillation
QC	Quality Control
QLCs	Quasi-Linear Convective Systems
QPE	Quantitative Precipitation Estimation
QPF	Quantitative Precipitation Forecasts
QVP	Quasi Vertical Profiles
R & D	Research and Development
R2O	Research to Operations
RAC	Radar & Applications Course
RAI	Research Associate I
RadTraQ	Radar Tracking of Quality Software
RaXPol	Rapid X-band Polarimetric
RCA	Root Cause Analysis
RDMA	Remote Direct Memory Access
RD-QVP	Range-defined quasi-vertical profile
RED	Radar Engineering and Development
REFS	Ensemble Forecast System
REU	Research Experience for Undergraduate Students
REUGS	Underrepresented Graduate Students Program
RF	Radio Frequency
RFI	Radio Frequency Interference
RFMD	Radio Frequency Management Division
RFTI	Red Flag Threat Index
RGB	Rio Grande/Rio Bravo Basin
RH	Relative Humidity
RHI	Range-Height Indicator
RIL	Radar Innovations Laboratory
RITC	Radar and Applications Course in the Cloud
ROC	Radar Operations Center
ROOTs	The R2O/O2R Tales
RPAR	Rotating Phased Array Radar

RQI	Radar Quality Index
RRDD	Radar Research and Development Division
RRFS	Rapid Refresh Forecast System
RTMA	Real-Time Mesoscale Analysis
RSI	Research Scientist I
S2S	Subseasonal-to-Seasonal
SAR	Stand-Alone Regional
SBC	Spectral Bin Classifier
SBES	Social, Behavioral, and Economic Sciences
SCT	Severe Convections Team
SDC	SOO-DOH Development Course
SE	Southeast
SFE	Spring Forecasting Experiment
SGP	Southern Great Plains
SHAVE	Severe Hazards Analysis and Verification Experiment
SHV	Simultaneous horizontal and vertical
SHT	Stormscale Hydrology Team
SIP	Secondary Ice Production
SLEP	Service Life Extension Program
SLR	Snow-to-Liquid Ratio
SMART-R	Shared Mobile Atmospheric Research and Teaching Radar
SNR	Signal-to-Noise Ratio
SO	Southern Ocean
SOOs	Science and Operations Officers
SOCRATES	Southern Ocean Cloud Radiation Transport Experimental Study
SoM	School of Meteorology
SP	Southern Plains
SPARC	The Space Science and Engineering Center Portable Atmospheric Research Center Facility
SPC	Storm Prediction Center
SPRT	Staggered Pulse Repetition Time
SPP	Stochastically Perturbed Parameterization
SQSS	Quasi-steady state supersaturations
SREF	Short-range Ensemble Forecast
SRI	Sponsored Research Initiative
SRW	Short-Range Weather
SS	Synoptic Snow

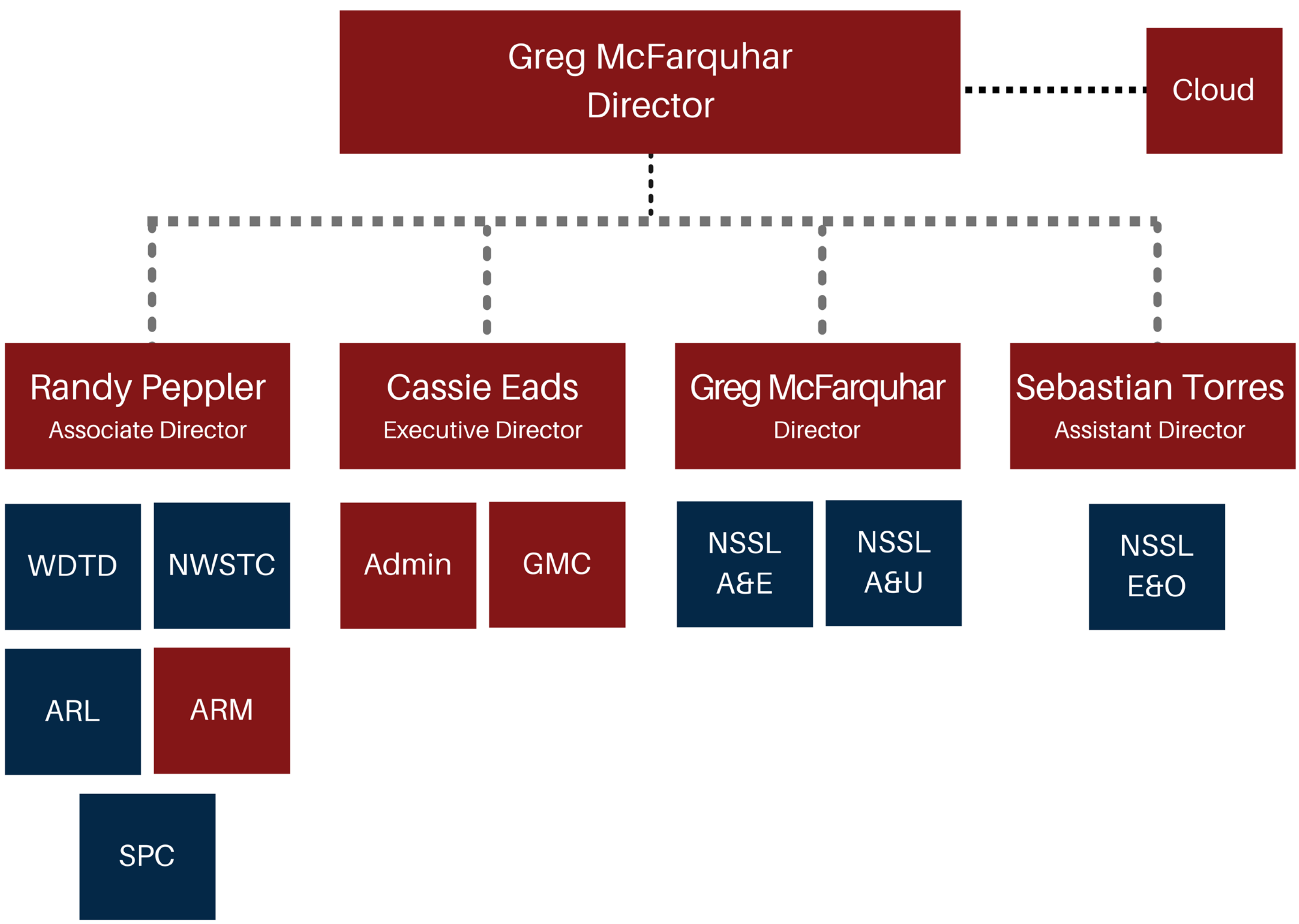
SST	Sea Surface Temperature
STD	Storm-top divergence
STEPS	Short-Term Ensemble Prediction System
StickNet	Portable in-situ surface weather stations
STORM	Student Tele-Operated Robotics Mission
SubX	Subseasonal Experiment
SUNY	the State University of New York at Albany
SVC	Streamwise Vorticity Currents
SWAMP	Soil Water Analysis Model Product
SWE	Snow liquid water equivalent
SZ-2	Sachidananda-Zrnic-2
TAC	Technical Advisory Committee
TAT	Transportation Application Team
Tb	Brightness temperature
TDA	Tornado Detection Algorithm
TDRs	Tail Doppler radars
THREDDS	Thematic Real-time Environmental Distributed Data Services
TIM	Threats-in-Motion
TLV	Tornado-like vortex
TORP	The tornado probability algorithm
TORUS	Targeted Observation by Radars and UAS of Supercells
TOTAL	Telemetry of Observed Total Accumulated Liquid
TPD	Ten Panel Demonstrator
TPT	Testbed and Prototype Team
TRACER	Tracking Aerosol Convection Interactions Experiment
TTU	Texas Tech University
TV	Tennessee Valley
TWIEP	Tornado Warning Improvement and Extension Program
UAM	Urban Air Mobility
UAS	uncrewed aerial/aircraft system
UAS	uninhabited aerospace systems
UCAR	University Corporation for Atmospheric Research
Uconn	University of Connecticut
UFS	Unified Forecast System
UFS-R2O	Unified Forecast System Research-to-Operations
UH	Updraft Helicity

URGE	Understanding Racism in Geosciences
USACE	United States Army Corps of Engineers
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
UTC	Coordinated Universal Time
VAD	Velocity-Azimuth Display
VBV	Veer-back-veer
VCP	Volume Coverage Patterns
VHF	Very High Frequency
Vlab	Virtual Lab
VorTech	Vortex Tornado Simulator
VORTEX	Verification of the Origins of Rotation in Tornadoes Experiment
VORTEX2	Verification of the Origins of Rotation in Tornadoes Experiment-2
VORTEX-SE	Verification of the Origins of Rotation in Tornadoes Experiment-Southeast
VSGC	Virginia Space Grant Consortium
WARA	Weighted Adaptive Range Averaging
WDSS	Warning Decision Support System
WDSS-II	Warning Decision Support System-Integrated Information System
WDT	Weather Decision Technologies
WDTD	Warning Decision Training Division
W2W	Watch-to-Warning
W2WEs	Watch-to-Warning Experiments
WES	Weather Event Simulator
WES II	Weather Event Simulator-II
WET	Weather Environment Thresholding
WFO	Weather Forecast Office
WILMA	West Texas Lightning Mapping Array
WOC	The Warning Operations Course
WoF	Warn-on-Forecast
WoFS	Warn-on-Forecast System
WPC	Weather Prediction Center
WRDD	Warning Research Development Division
WRF	Weather Research and Forecast
WRFIA	Weather Research and Forecasting Innovation Act
WSR-57	Weather Surveillance Radar-1957
WSR-88D	Weather Surveillance Radar-1988 Doppler

WTC	Wind Turbine Center
WTLMA	West Texas Lightning Mapping Array
Z	Reflectivity
ZDR	Differential reflectivity

APPENDIX C: ORGANIZATIONAL STRUCTURE, PERSONNEL AND GRADUATE STUDENTS

CIWRO's organizational structure is summarized here. Names in red or white type are CIWRO employees. Names in blue type are federal technical advisors. Blue division blocks are principally funded by Cooperative Agreement, whereas red division blocks are funded outside the Cooperative Agreement.



WDTD

Randy Peppler
Associate Director

Team 1	Team 2	Team 3
A. Wood B. Boustead, J. Ladue, R. Prentice	D. Morris M. Magsig	C. Spannagle Fed TA
A. Bates K. Christian L. Elizalde M. Lamkin M. Paulus (FDTD) C. Spannagle E. Vasquez	S. Corfidi D. Creveling S. Edwards M. Lowe R. Pajela H. Taning Kaffo	J. Bunker S. Boyd T. Enzensperger (FDTD) H. Wells A. Woodward

NWSTC

Randy Peppler
Associate Director

OCLO
R. Peppler (interim) J. Keeney, J. Zeltwanger
J. Niemeyer

NSSL E&O

Sebastian Torres
Assistant Director

Advanced Radar Techniques

S. Torres

N. Boeckman
C. Curtis
R. Estes
S. Gregg
R. Jagannath
D. Mirković
F. Nai
C. Salazar Aquino

Field Observations and Remote Sensing

S. Stough

T. Bell
L. Bunting
J. Gebauer
T. Segales
M. Stock
E. Tirone

Radar Engineering Development

P. Servello

A. Zahrai
N. Zemlin

ACME

J. Brogden
T. Smith

K. Cooper
G. Fisher
C. Langston
T. Miller
M. Taylor
R. Toomey

NSSL E&Q Students

Sebastian Torres
Assistant Director

Field Observations and Remote Sensing Students

S. Stough

J. Berry (GRA)
M. Bowen (UG)
C. Schneider (GRA)
A. Al Tasim (GRA)
M. Ammon (UG)
E. Stroberg (UG)
J. Lawson (UG)
A. Cotton (UG)
J. Simms (UG)
A. Quiroz (UG)
A. Raaijmakers (UG)

NSSL A&U

Greg McFarquhar
Director

Steve Martinaitis
Senior Research Associate

Precipitation Radar

S. Martinaitis

A. Arthur
P. Bukovcić
S. Cocks
K. Elmore
N. Liu
V. Melnikov
D. Meyer
L. Tang

Severe Convective Radar

T. Schuur

J. Boettcher
L. Dunnavan
J. Hu
M. Johnson
J. Krause
A. Ryzhkov
B. Smith
K. Tuftedal
P. Zhang

S2S and Extreme Weather

B. Schenkel

W. Cui

Storm-Scale Processes

J. Segall

R. Miller
T. Sandmael
M. Satrio

NSSL A&U Students

Steve Martinaitis
Senior Research Associate

S2S and Extreme Weather

B. Schenkel

M. Hosek (UG)
I. Jernigan (GRA)
R. Mendeke (UG)
S. Mullinix (UG)
K. Wheeler (GRA)

Severe Convective Radar

T. Schuur

C. Berry (UG)
E. Blumenauer (GRA)
T. Davis (UG)
S. Southward (GRA)

Storm-Scale Processes

J. Segall

D. Candela (GRA)
M. Diedrichsen (GRA)
R. Moore (GRA)
L. Pounds (GRA)
R. Saba (GRA)
M. Schneider (GRA)
T. Pardun (GRA)

NSSL A&EU

Greg McFarquhar
Director

Nusrat Yussouf
Senior Research Scientist

Severe Convective Probabilities and Impacts

K. Knopfmeier

K. Britt
M. Flora
E. Loken
P. Skinner
C. Satrio

Visualization

A. Campbell

B. Kraninger
J. Madden
J. Monroe
R. Steeves

Data Assimilation and Modeling

N. Yussouf

T. Jones
C. Kerr
F. Ma
J. Martin
B. Matilla
J. Tweedie
D. Stratman
Y. Wang

Aviation, Hydrology, and Winter Probabilities & Impacts

H. Reeves

J. Duarte
J. Dufort
A. Rosenow
D. Tripp
A. Werkema

SBES

H. Obermeier

D. Hogg
T. Maciag
M. Silcott

NSSL A&EU Students

Nusrat Yussouf
Senior Research Scientist

Severe Convective Probabilities and Impacts

K. Knopfmeier

D. Crutchfield (UG)
A. Dringus (UG)
R. Mwakyoma (UG)
J. Widanski (UG)
A. Dixon (GRA)
W. Faletti (GRA)
R. Martz (GRA)

SBES

H. Obermeier

J. Tessitore (UG)

Aviation, Hydrology, and Winter Probabilities & Impacts

H. Reeves

B. White (GRA)

AGS GMC

Cassie Eads
Executive Director

GMC

J. Guin

M. Dukes
J. Foucher

ARM

Randy Peppler
Associate Director

DQ Office

R. Peppler

C. Godine
K. Kehoe
M. Li
A. Sockol

ARM Students

Randy Peppler
Associate Director

DQ Office

A. Sockol

T. Anderson (UG)
R. Auringer (UG)
L. Bush (UG)
H. Cavender (UG)
J. Dunning (UG)
D. Moak (UG)
K. Scarberry (UG)
V. Tiradoegas (UG)
E. Whatley (UG)
E. White (UG)

SPC

Randy Peppler
Associate Director

Team 1	Team 2
D. Harrison I. Jirak	D. Jahn I. Jirak
C. Nixon J. Picca K. Thiel J. Vancil	M. Baldwin K. Hoogewind J. Milne A. Wade

SPC Students

Randy Peppler
Associate Director

Team 1
D. Harrison
B. Fellman (GRA) G. Talkington (GRA)

Admin

Cassie Eads
Executive Director

CIWRO Admin

C. Eads

M. Campbell
A. Price
T. Riley

Admin Students

Cassie Eads
Executive Director

ROC Task III

C. Eads

M. Kovisto (UG)
B. Boeth (UG)
M. Funck (UG)
B. Sherman (UG)

Cloud

Greg McFarquhar
Director

Cloud/Other

G. McFarquhar

A. Dzambo
N. Dhangar (PD)

Cloud Students

Greg McFarquhar
Director

Cloud

G. McFarquhar

S. Ameri (GRA)
N. Amundsen (GRA)
P. Brechner (GRA)
P. Davis (UG)
J. Douglas (UG)
D. Mise (GRA)
Q. Niu (GRA)
S. Patil (GRA)
E. Pruitt (GRA)
A. Richter (GRA)
Z. Xia (GRA)

APPENDIX D: TECH TRANSFERS

Oct. 2021- present

Weather Radar and Observations Tech Transfers

Name: SfcHCA
Description: This algorithm diagnoses precipitation type at the surface using a sophisticated 1-D microphysics model based on ambient thermodynamic information from hourly model data. Particles are diagnosed from polarimetric RD-QVPs, where microphysics output is coupled with low-level hydroclassification output to create a precipitation type product valid at the ground. A key advanced feature is the adjustment to hourly model temperature using sub-hourly RD-QVP melting layer identification.
Status: This algorithm has been transferred to the NWS and is scheduled for deployment.

Name: Azimuthal Shear (AzShear)
Description: This algorithm provides real-time quantification of the azimuthal shear gradients in radial velocity data that are associated with rotational features, such as mesocyclones and tornadoes, that are sampled by the WSR-88D radar network. AzShear forms the backbone of the TORnado Probability Algorithm (TORP) and New Mesocyclone Detection Algorithm (NMDA) discussed below. AzShear has been developed as part of the ROC/NSSL Tech Transfer with the end user being NWS partners.
Status: Transitioned, but not in operations. The algorithm has been delivered to the ROC, and is undergoing testing before operational deployment.

Name: Quasi-Vertical Profiles (QVP) and the Range-Defined Quasi-Vertical Profiles (RD-QVP)
Description: These algorithms are new methods to view radar data. Created from an elevation or volume of radar data the presentation is in Time-Height format with time on the x-axis and height on the y-axis. The computation of this output averages a large amount of data at the same height and allows a detailed view of the vertical profile for the radar moments and variables. Vertical profiles of radar data can be used to infer changes between snow, rain, and ice.
Status: These two algorithms have been delivered to the ROC and implemented. The outputs are available in real time.

Name: QZdr Calibration (QZdrCal) -
Description: Accurate Zdr calibration is a long term issue for the WSR-88D radar. Because the radar's elevation is physically limited to a maximum of 20 degrees, standard Zdr calibration methods using a birdbath scan are impossible. With the availability of RD-QVP outputs now on the radar, a method was developed to utilize these outputs to accurately determine the calibration for Zdr. The outputs from this algorithm are available in real time and are being evaluated for accuracy on the network of radars. Originally developed for the warm season, the algorithm has been adapted to run on cold season data and is now considered an “all” season algorithm.
Status: This algorithm has been delivered to the ROC.

Name: New Melting Layer algorithm (newML) -
Description: Identification of the melting layer in radar data is necessary for a variety of other algorithms. The region where the snow melts into rain is normally consistent, but cold season frontal systems can have tilted or discontinuous melting layers. The original melting layer algorithm was prone to significant errors in cold season frontal situations. A new technique and algorithm were developed to identify the melting layer signature at the lowest elevation levels and to combine these detections with model data. The process results in melting layer information at each gate, whereas the original method only outputs melting layer information for each radial. As such, the differences required modifications to several algorithms that use melting layer information.
Status: This algorithm is being adapted for use on the WSR-88D radar.

Name: Range Oversampling
Description: This is a signal-processing technique that can be used to improve the quality of NEXRAD data and thus help improve forecaster interpretation and the performance of algorithms. This technique was approved by the NEXRAD Technical Advisory Committee for implementation on the NEXRAD network.
Status: The technique is transitioned but not in operations.

Name: Updates to the SZ-2 (Sachidananda-Zrnic-2) Algorithm
Description: These are important algorithmic updates for a signal-processing technique that is used to improve the quality of NEXRAD data and thus help improve forecaster interpretation and the performance of algorithms.
Status: This technique is operational on the NEXRAD network. The algorithmic updates are transitioned but not in operations.

Name: Updates to the CLEAN-AP (Clutter Environment Analysis using Adaptive Processing) Algorithm
Description: These are important algorithmic updates for a signal-processing technique that is used to improve the quality of NEXRAD data and thus help improve forecacolorster interpretation and the performance of algorithms. This technique being evaluated by the Radar Operations Center for future implementation on the NEXRAD network.
Status: The algorithmic updates are transitioned but not in operations.

Name: Updates to the HSE (Hybrid Scan Estimator) Algorithm
Description: These are important algorithmic updates for a signal-processing technique that is used to improve the quality of NEXRAD data and thus help improve forecaster interpretation and the performance of algorithms. This technique being evaluated by the Radar Operations Center for future implementation on the NEXRAD network.
Status: The algorithmic updates are transitioned but not in operations.

Name: MRMS System
Description: Many updates are continually being made to MRMS to ensure that is stays a relevant and sustainable system for the future. Below, the status of updates of various versions are summarized.
Status:
v12.1.7: delivered to NCO 10/29/2021 - operational 12/06/2021
v12.2-v12.2.3: delivered to NCO 01/24/2022 - 04/12/2022 - operational ~ 04/29/2022
- Added new Canadian S-band radars and made improvements to gauge processing, several Severe and Hydromet products.

v12.2.4: delivered to NCO 06/10/2022 - operational ~ 06/10/2022
- Added last of Canadian S-band radars (they did a staged rollout) update Hydromet products and RIDGE2 meta data

v12.2.5: delivered to NCO 03/01/2023; operational ~ 08/23/2023
- Removed ANC products, RIDGE2 updates, Severe and Hydromet product updates

v12.2.6: delivered to NCO 09/29/2023; operational 11/28/2023
- Restore Canadian S-band radars after ECC changed their scan strategy and their data would no longer work in MRMS, FLASH, Severe and Hydromet product updates

v12.2.7: delivered to NCO ~ 12/14/2023; operational 01/10/2024
v12.2.8: delivered 05/22/2024; operational ~ 07/9/2024
- Added new radar KHDC, update Severe, Hydromet and FLASH products

v12.2.9: delivered 09/27/2025; operational ~ 10/15/2025
For each year, the Salt River Project's MRMS installation was also updated - once a year around the Springtime in preparation for their monsoon season. Typically, the update is to whatever the latest MRMS build was at the time.

Name: MRMS Operational Product Viewer
Description: The MRMS Operational Product Viewer is a web-based tool that displays a rolling archive of real-time operational MRMS products dating back to October 2020 that are distributed by the NWS NCEP Central Operations (NCO). Though made available before October 2021, the operational viewer is hosted at the NSSL and undergoes continuous new development and updates. The viewer is utilized by numerous users in the NWS, NOAA, NASA, and other organizations, including private companies.
Status: In Operation

Name: Dual Pol Synthetic Radar Only QPE (Q3DP)
Description: MRMS specific attenuation based Q3DP QPE exhibited significant error biases with mesoscale convective systems having strong deep convection and a significant area of stratiform rain present. A wet bias was noted in the deep convective areas and at times a dry bias was also present in the stratiform rain. This was due to the estimation, via the slope of Zdr to Z, of the parameter alpha which is used in calculating the path integrated attenuation (PIA); the slope estimate of alpha results in a mean value for the radar field-of-view (FOV) where the two rain regimes are present. This results in an alpha value that is too high (low) in deep convection (stratiform) rain; as alpha is linearly related to rain rates for S-band radars, significant QPE biases can occur.
Status: Using dual pol information, a rate adjustment was developed that mitigates these biases with the technology transitioned into NWS operations by May 2022. The end-users are primarily NWS forecasters.

Name: Dual Pol Synthetic Radar Only QPE (Q3DP)
Description: MRMS specific attenuation based Q3DP QPE also exhibited significant biases when stratiform rain was predominant in the radar FOV; this was due to the use of a single alpha value used when calculating specific attenuation fields. The value used could result in a QPE wet (dry) bias for Continental (tropical) like stratiform rain. Using dual pol information, a method was developed that assigns a value for alpha that better reflects the rain regime present in the radar field-of-view; as alpha is linearly related to rain rates for S-band radars this technique mitigates the observed biases.
Status: The algorithm has been running in a real-time environment on the vMRMS research testbed and is currently ready for transition into NWS operations.

Name: Meteorological Phenomena Identification Near the Ground (mPING)
Description: The mPING system uses a mobile application that allows citizen scientists to report meteorological phenomena in their area, including precipitation type, hail, flooding, wind, etc. The use of crowdsourced data allows for the use of various studies of products as well as provide verification to the NWS for events, including severe weather.
Status: The mPING transition plan for the NWS is complete and has been finalized. NWS forecasters are already using this product and it is even available to them in AWIPS.

Name: Probability of Sub-freezing Roads (ProbSR)
Description: An hourly CONUS-wide product that provides a 0-100% probability road temperature are subfreezing.
Status: fully read to transition to NWS version of MRMS, running live on MRMS system at NSSL, transitioned to WPC for internal use on prognostic model output.

Name: Spectral Bin Classifier (SBC)
Description: An hourly CONUS-wide analysis of surface precipitation type.
Status: fully read to transition to NWS version of MRMS, running live on MRMS system at NSSL

Name: Helicopter Emergency Medical Services (HEMS) mosaic
Description: A CONUS-wide mosaic of composite reflectivity for the lowest 0 to 4 km above ground level. It is updated every 2 minutes and provides flags for locations that have no radar coverage in this layer.
Status: fully read to transition to NWS version of MRMS, running live on MRMS system at NSSL

Name: Flight layer composite reflectivity
Description: 5 CONUS-wide mosaics of composite reflectivity for select flight layers (18 to 25 kft, 25 to 30 kft, 30 to 35 kft, 35 to 40 kft and 40+ kft) that are updated every 2 minutes.
Status: fully read to transition to NWS version of MRMS, running live on MRMS system at NSSL

Name: Near real-time derecho identification
Description: A technology that objectively identifies in real-time wind intensity of mesoscale convective systems (MCSs) and the formation of derechos. Based on an analysis of thousands of MCSs, this algorithm tracks MCSs, maps out and ranks damaging-wind-swath potential, and identifies those that qualify as derechos.
Status: Available for use in operations daily. This technology is currently used daily by SPC forecasters to help identify the development of a significant damaging wind event.

Name: StormCell identification and Tracking (MCIT)
Description: The current method to identify and track storms (SCIT) was developed in 1998 and uses storm centroids. All modern methods of storm identification and tracking use storm areas. Multi-Cell Identification and Tracking (MCIT) is a watershed based method that uses the Vertically Integrated Liquid (VIL) product as input to determine the area for each storm. The tracking of the cell through time is a separate scientific method and we have applied an overlapping technique for use on the ORPG.
Status: The delivery of this algorithm is being used as a protype to determine how to replace the 1998 SCIT outputs and to determine the amount of work to do so.

Name: New Mesocyclone Detection Algorithm (NMDA)
Description: Provides improved real-time radar-based identification of mesocyclones from WSR-88D data. The NMDA was developed by Brandon Smith as part of the ROC Tech Transfer with the end user being NWS partners.
Operational status: Fully ready to transition

Name: Freezing Rain Accumulation National Analysis (FRANA)
Description: This is a CONUS wide analysis of the hourly rate of accumulation of ice due to freezing rain/freezing drizzle. Hourly accumulations are then summed to provide 6-, 12-, 24-, and 72-h running totals. The algorithm provides the accumulation both for flat ice (i.e., the rate of accumulation on a flat surface) and radial ice (i.e., the rate of accumulation on a radial surface such as a power wire or tree limb).
Status: fully ready to transition, running live on experimental MRMS system at NSSL, grids are streamed to NWS offices and used in operations.

Name: Lightning Data Webpage
Description: A new lightning data webpage was launched on the SPC public website in 2022. This webpage provides an interactive interface to view and interrogate lightning data, including heat maps and time series displays.
Status: The website is fully operational and available to the public at https://www.spc.noaa.gov/climo/dataviewer/, and additional datasets are expected to be added later in 2025.

Name: HREF Calibrated Thunder Guidance
Description: The HREF Calibrated Thunder Guidance is a suite of lightning forecast products derived from the High-Resolution Ensemble Forecast System (HREF) which predict the probability of at least 1 cloud-to-ground lightning flash within 12 miles of a location over a specified 1-h, 4-h, or 24-h time period.
Status: The guidance is operational within the NWS and available to the public via the NOAA Operational Model Archive and Distribution Service (NOMADS) and other distribution services. The HREF Calibrated Thunder Guidance serves as a first guess for SPC forecasters when drawing their general thunderstorm outlooks.

Name: HREF Lightning Density Guidance
Description: The HREF Lightning Density Guidance is a suite of forecast products derived from the High-Resolution Ensemble Forecast System (HREF) that predict the likelihood of at least 25, 50, 100, or 200 cloud-to-ground lightning flashes occurring within 12 miles of a location during a specified 4-h time period.
Status: This guidance is currently operational internally at SPC and is used to assess dry-thunder potential when drawing the fire weather outlooks. The HREF Lightning Density guidance is also in the process of transitioning to NWS-wide operations where it will be publicly accessible through operational distribution channels later in 2025.

Name: Tropospheric Remotely Observed Profiling via Optimal Estimation (TROPoe)
Description: The TROPoe software package retrieves thermodynamic profile data from ARM's infrared spectrometers, which are deployed at ARM's fixed and mobile sites. Infrared spectrometers are highly specialized instruments and few people understand how to use the data in their analyses. TROPoe adds value to the infrared spectrometer data by retrieving thermodynamic profiles, thereby increasing the number of researchers using this data and leading to new and more advanced scientific results.
Status: software is operational at DOE/ARM facilities

Mesoscale and Storm-scale Modeling Tech Transfers
Name: NSSL-Convection Allowing Models (CAMS)
Description: A suite of experimental model runs completed by CIWRO/NSSL and the NOAA/Global Systems Laboratory designed to test emerging numerical weather prediction development. These runs are displayed on the NSSL-CAMS webpage (https://cams.nssl.noaa.gov) and post-processed model output is provided to NOAA/NWS operational centers and forecast offices, the Cooperative Institute for Research in the Atmosphere, and Pivotal Weather LLC . The output from these runs is intended to be used by NWS and operational center forecasters to aid in forecast product generation (e.g., the SPC Day 1 Convective Outlook), but is also available to the general public via the NSSL-CAMS and Pivotal Weather webpages.
Status: internal operational use

Forecast Applications Improvements Technology Transfers

Name: Warn-on-Forecast System
Description: WoFS is a storm-scale numerical weather prediction ensemble analysis and forecast system that makes probabilistic predictions of individual thunderstorms and their hazards, such as wind speeds, hail size, rainfall, and updraft helicity and vertical vorticity (measures of storm rotation). The probabilistic tools WoFS provides align with the FACETs paradigm for severe weather at 0–6 hours. WoFS aids forecasters in communicating uncertainty information for specific hazards at scales ranging from watch to warning and is the first storm-scale ensemble of its kind. The end users are NOAA National Centers (i.e. SPC, WPC and AWC) and NWS WFOs for severe weather and heavy rainfall operations.
Status: Fully ready to transition. CIWRO/NSSL is currently training/assisting NWS/OSTI to run cb-WoFS on their Microsoft Azure account. NWS/OSTI will begin running WoFS from May 2025. For more information, please visit: https://vlab.noaa.gov/web/osti-modeling/warn-on-forecast-system. The national centers SPC, WPC, AWC and NWS Weather Forecast Offices are using the products.

Name: Automated Convective Sigmets (C-SIGs)
Description: This is a first-guess of convective sigmet polygons produced at 10-min intervals.
Status: fully ready to transition, running live on experimental MRMS system at NSSL. Algorithm is being evaluated in NWS testbeds.
Name: Calibrated tornado forecast guidance
Description: A probabilistic forecast guidance product was created that leverages a statistical relationship among tornado frequency and a storm index that incorporates environmental and storm-scale fields of the High Resolution Ensemble Forecast system.
Status: A calibrated tornado guidance product is currently available daily to SPC forecasters, which highlights areas of various probability thresholds of predicted tornado occurrence within a 24-hour forecast period starting at 00z and 12z.

Name: NWS Probabilistic Hazard Information (PHI) Evaluation
Description: Experimental, autonomous hazard-based PHI is being distributed to NOAA/NWS for evaluation in operations as IDSS guidance. PHI is a storm-based product derived from machine-learning (ML) algorithms (ProbSevere, TORP, and ProbLightning) to provide continuously updating, spatiotemporal guidance that conveys motion, timing, and likelihood of severe weather hazards (thunderstorm wind, hail, tornado, and lightning). Forecasters load placefile URLs into Gibson-Ridge 2 Analyst (GR2) to evaluate real-time Severe, Tornado, and Lightning feeds, and provide feedback to researchers via a designated Slack channel. Resources for forecasters are hosted on https://phi.nssl.noaa.gov/, which includes general information, how to request and access real-time placefile URLs, and a current map of real-time operating domains.
Status: transitioned but not in operations

Name: WoFS-PHI (Warn-on-Forecast System - Probabilistic Hazard Information
Description: An ML product designed to predict the likelihood of severe weather hazards (wind, hail, and tornadoes) at lead times of 30 minutes to 4 hours based on data from Prob-Severe and WoFS. It is intended to be used by NWS and SPC forecasters to help them forecast and message the severe weather threat between watch and warning issuance. WoFS-PHI is displayed in real-time in the cloud-based (cb)-WoFS Viewer (https://cbwofs.nssl.noaa.gov/Forecast) and is part of the suite of WoFS postprocessing products.
Status: internal operational use

Name: TORnado Probability Algorithm (TORP)
Description: Provides probabilistic real-time guidance of a current or future tornado using a machine learning model applied to WSR-88D data. TORP was developed by Thea Sandmæl as part of the ROC Tech Transfer with the end user being NWS partners.
Operational status: In operations. TORP has not been formally transferred to the NWS, but NWS WFOs are already using TORP in operations as part of the beta testing of the PHI tool.

Name: Loken RF Severe Weather Probabilities
Description: An ML algorithm designed to predict the 24-h/day 1 likelihood of severe hail, wind, and tornadoes based on data from the High-Resolution Ensemble Forecast System Version 3 (HREFv3). It currently runs twice per day (after the 00z and 12z model data come in) and is available to SPC forecasters (the intended users) internally during their operational shifts. They use it as guidance for constructing their day 1 convective outlooks.
Status: internal operational use

Name: WoFS-based ML Hazard Guidance
Description: A gridded ML-based guidance product designed to predict the occurrence of severe wind, severe hail, and tornadoes at lead times of 2-6 hours. It has been evaluated in the HWT Spring Forecasting Experiment since 2021 and is displayed in real-time in the cb-WoFS viewer (https://cbwofs.nssl.noaa.gov/Forecast). It is intended to be used by NWS and SPC forecasters to help them forecast and message the severe weather threat between watch and warning issuance.
Status: internal operational use

Name: Combined ROC NMDA/TORP AWIPSII Plugin
Description: This plugin for the AWIPSII weather forecasting and display software combines the ingest and visualization of data from the updated New Mesoscale Detection Algorithm (NMDA) and the Tornado Probability Detection Algorithm (TORP). Incoming NMDA/TORP data files are ingested into the AWIPSII data framework and are then available for analysis via distinct object visualizations and inspections depending on the record being displayed. This plugin was developed and delivered to the Radar Operations Center (ROC) by Jonny Madden in FY22.
Status: Transitioned but not in operations

Name: Sounding Database Version 2
Description: A new version of SPC's sounding webpage was transitioned to the public website in 2022. This new version introduced increased customization options and dynamic

graphs to allow weather enterprise users to more fully investigate the underlying data.
Status: The website is fully operational and available to the public at https://www.spc.noaa.gov/exper/soundingclimov2/.

Name: Quantitative Tornado Probabilities and Count Predictions
Description: This system applies the statistical definitions of SPC severe weather forecasts to estimate the unconditional likelihood of an EF2+ tornado for a given convective outlook. The system also estimates the most likely and worst-case number of tornadoes that would be expected in a given convective outlook.
Status: This system is operational internally at SPC and is being used to help calibrate forecasters to a new conditional intensity paradigm.

Name: First-Guess Watch Guidance
Description: The First-Guess Watch Guidance is a machine learning model trained on the High-Resolution Ensemble Forecast System (HREF) that predicts when and where a Tornado or Severe Thunderstorm Watch will be needed out to 48-hours in advance of severe weather.
Status: The guidance generates deterministic county-based watch recommendations with the intent to provide at least 3-hours lead time prior to the first severe weather report. This product is operational internally at the SPC and has been used to improve situational awareness, plan the timing of watch issuances, and inform staffing considerations on active severe weather days.

Social and Socioeconomic Impacts of High-Impact Weather Systems

Name: Quantitative Societal Impacts System
Description: The Quantitative Societal Impacts System is a statistical modelling system that simulates tornado events to estimate potential societal impacts. The model is built upon the Quantitative Tornado Probabilities and Count Predictions system described above and uses the current SPC convective outlook to estimate the most likely and worst-case societal impacts (e.g., infrastructure impacts, casualties, and fatalities) of a predicted tornado event.
Status: The system is currently operational internally at SPC and simulations are being shared with NWS Southern Region. Future operational transitions are expected to further share the simulations with FEMA and the Red Cross.

Patents

Patent: Machine Learning Approach for Intelligent VAD Wind Estimation with Polarimetric Radars
Inventors: Precious Jatau (ARRC), Tian You Yu (ARRC), Valery Melnikov (OU CIWRO)
Description: This work utilizes the velocity azimuth display (VAD) information from radars along with a machine learning algorithm to identify birds that are active fliers. By identifying biological scatter such as flying birds within the VAD, the machine learning algorithm can use this information to better remove the non-meteorological radar echoes created by them to improve data quality.
Status: Patent status is pending.

APPENDIX E: AWARDS

Announced 2025

CIWRO Annual Awards

Scientific and Engineering Research and Development Award
Thomas Jones
“Dr. Jones successfully developed the Warn-on-Forecast System for fire weather prediction (WoFS-Smoke) and evaluated the system in NOAA’s Fire Weather Testbed and Norman Forecast Office. Dr. Jones’ extraordinary technical expertise and dedication transforms how WoFS is applied to fire hazards, which is critical for public safety and environmental protection.”

Scientific and Engineering Research and Development Award
Kevin Thiel
“Mr. Kevin Thiel is awarded the CIWRO award in Scientific and Engineering Research and Development for his exceptional initiative and leadership in organizing and executing the 2024 HWT Satellite Convective Applications Experiment. His efforts have had a major impact on the transition of satellite research into NWS operations.

CIWRO Research to Operations Award
Andrew Wade
"Dr. Andrew Wade is awarded the CIWRO R2O award because his technology addresses an expressed NWS need for the timely ability to diagnose derecho occurrence, which represents an extraordinary example of collaboration with operational forecasters. His work has been cited in BAMS, and his technology is already making an impact operationally."

Outreach/Program Management & Leadership/Service Award
Annette Price
“Annette Price is awarded the CIWRO Outreach/Program Management & Leadership/Service award for her dedication and excellent performance at organizing and delivering high-impact outreach events to the broader Oklahoma community and to schools throughout the state of Oklahoma.”

Community Awards

AMS Radar Scientific and Technological Activities Commission (STAC) Distinguished Accomplishment Award
Alexander Ryzhkov
For recurrent and impactful contributions to the AMS radar and broader weather community that have transformed and shaped fundamental research and operations.

AMS Special Award for contributions in visualizations of web-based hodographs
Cameron Nixon
2025 Oklahoma Emergency Management Association (OEMA) Challenge Coin

David Hogg, Miranda Silcott, Erick Loken, Claire Satrio, Rebecca Steeves, Adrian Campbell, Jonny Madden, Justin Monroe, Ryan Martz, Thea Sandmael, and Patrick Skinner
For the group involved in running the 2024 HWT Watch-to-Warning Experiment.

Student Awards

First Among Abstracts, European Radar Conference
Zeqian (Hazel) Xia

First Prize in Poster Presentations for the 12th Conference on the Meteorological Application of Lightning Data at AMS 2025
Malachi Bowen

Second Place Best Student 29NWP Poster Presentation at the AMS 105th Annual Meeting
Madeline Diedrichsen

Third Place Best Student Oral Presentation for the 33rd Conference on Weather Analysis and Forecasting/29th Conference on Numerical Weather Prediction at the 105th AMS Annual Meeting
Lauren Pounds
"Analysis of Southeast U.S. Tornadic and Non-tornadic Environments of Varying Storm Modes using Observed Soundings from the VORTEX-SE, Meso18-19, and PERiLS Field Campaigns”

Third Place Best Student Oral Presentation at AMS Annual Meeting - 33rd Conference on Weather Analysis and Forecasting (WAF)
Jacob Widanski

2025 Sponsored Award - The Ohio Academy of Science’s Buckeye Science & Engineering Fair, Regeneron International Science & Engineering Fair Qualifying Finalist
First Place in Earth and Environment Science - Northeastern Ohio Science and Engineering Fair
Kira Florek (Mentor High School, OH / CIWRO mentee)

Texas A&M Student Research Week's Best Earth and Physical Sciences Poster
Kate Stapleton (CIWRO/NSSL Hollings student from Texas A&M)

Announced 2024

U.S. Department of Commerce Awards

DOC Gold Medal
Derek Stratman, Montgomery Flora, Miranda Silcott, Patrick Skinner, Thomas Jones, Yunheng Wang, Nusrat Yussouf, Joshua Martin, Kent Knopfmeier, Brian Matilla, Chris Kerr, Kimberly Hoogewind, and Eric Loken.
Contributions of CIWRO & NOAA scientists led to the NSSL FRDD winning the Gold Medal. The Gold Medal is the highest honor that can be bestowed by DOC and is awarded to individuals or groups for exceptional service for noteworthy or superlative contributions that have a direct and lasting impact.

Photo: CiWRO researchers working on WoFS receive recognition from CIWRO and NSSL leadership for the Gold Medal won from the U.S. Department of Commerce. Photo by CIWRO Outreach Coordinator Annette Price.

CIWRO Annual Awards

Award for Outstanding Publication
Thea Sandmael, Brandon Smith, Jonathan Madden, Rebecca Steeves and Kim Elmore
For developing a machine learning model for probabilistic tornado detection that demonstrates how machine learning improves radar-based tornado detection compared to current operational methods.
(other co-authors include Anthony Reinhart, Isaiah Schick, Marcus Ake, Skylar Williams and Tiffany Meyer)

Outstanding Achievement in Outreach, Education, or Service by an Individual
Andy Wood
"For his unwavering dedication, exceptional leadership, and invaluable contributions to CIWRO exemplifying his extraordinary commitment to the meteorological research and operations communities. He is identified as the 'WDTD Dad.' "

Outstanding Achievement in Research or Research Support
Joseph Trujillo Falcón
"For his groundbreaking work in bilingual risk communication and his instrumental role in transforming the way weather information is disseminated across NWS. Joseph has enhanced crisis communication through his unyielding dedication, pioneering research and impactful contributions."

Award for Outstanding Publication
David Harrison
"For expertly and clearly crafting a WAF article documenting skillful calibrated, probabilistic thunderstorm guidance based on the HREF, which is the operational NWS standard for thunderstorm forecasting."

Outstanding Achievement in Research or Research Support
Joshua Martin
"Mr. Martin led an extraordinarily successful project of moving the experimental Warn-on-Forecast System to a more efficient cloud-based platform (cb-WoFS). Mr. Martins' technical expertise, dedication and leadership enabled him to reach the goal two months ahead of schedule, allowing cb_WoFS to support the NWS and 2022 Spring Forecasting Experiments."

Outstanding Achievement in Research or Research Support
Jiaxi Hu and John Krause
"For their work in developing a novel differential reflectivity (ZDR) calibration algorithm using dry aggregated snow, in successfully demonstrating the advantages of this algorithm, and providing the algorithm to the ROC for operational implementation. This work is an excellent example of research-to-operations success."

OU Awards

Greg McFarquhar: George Lynn Cross Research Professor

OU College of Atmospheric and Geographic Sciences Awards

Superior Performance
Heather Reeves

Excellent Performance
Thea Sandmaeal, Patrick Skinner
Outstanding Performance
Kevin Thiel, Joshua Martin, Andrew Wade, Steve Martinaitis

Community Awards

National Weather Association (NWA) Member of the Year
Alyssa Bates

2024 Oklahoma Emergency Management Association Volunteer of the Year
David Hogg

2024 Southwest Region Emergency Management Volunteer of the Year
David Hogg

2024 Education and Career Development Award from the Boys & Girls Clubs of America's Oklahoma Area Council
For "Five Nights of Eddies: Surviving Tornadoes, Hurricanes and Other Severe Weather"
Those who contributed to the program's success: Annette Price, Cassie Eads, Michael Stock, Jackie Ringhausen, Rachel Miller, Addison Alford, Joseph Trujillo-Falcon, Erika Pruitt, Andy Wade, Adam Werkema, Lydia Bunting, DaNa Carlis, Jill Hardy, Andy Wood, Dale Morris, Alyssa Woodward, Chris Spannagle, Alex Zwink, Mandi Campbell, Tanya Riley, Amelia Cook, Katherine Moore & Greg McFarquhar

The STEM enrichment camp for middle-schoolers was made possible through funding from the Oklahoma State Regents for Higher Education and a partnership with the Boys and Girls Club of Norman.

Editor's Award by the *Advances in Atmospheric Sciences* journal
Valery Melnikov
"For providing timely, rigorous, and concise feedback in a professional manner."

Student Awards

Edwin and Lottie Kessler Memorial Endowed Scholarship in Meteorology
Lucas Bush

Thomas Julian Lockhart Scholarship in Meteorological Measurements & Observing Systems
Evan White

SoM Director's Recognition for Outstanding Service to the Department as an Undergraduate Student
Isaac Medina

2023 Outstanding Student Presentation Award for 2023 Fall AGU presentation
Saurabh Patil

Runner-up, Best Student Paper 24th Conference of Aviation, Range and Aerospace Meteorology
Jordan Tweedie

Douglas Lily Award for Best Ph.D. Manuscript/Publication
John D'Alessandro

SoM Directors' Recognition for Outstanding Service to the Department as a Graduate Student
Bobby Saba

Richard J Doviak Award
Morgan Schneider

Yoshi Sasaki Award for Best M.S. Manuscript/Publication
Lauren Pounds

Mark & Kandi McCasland Award for Outstanding Undergraduate Research Paper
Matthew Ammon

Undergraduate Academic Achievement Award
Evan White

Undergraduate Academic Achievement Award
Andrew Kenny

Undergraduate Achievement Award
Parker Davis

OU3 Memorial Meteorology Endowed Scholarship
Jonathan Douglas

Runner-up, Best Student Paper and Presenter at the AMS Annual 24th Conference of Aviation, Range and Aerospace Meteorology
Jordan Tweedie

OU College of Atmospheric & Geographic Sciences Outstanding Senior Second Alternate 2024-2025
OU Campus Awards - Campus Life Award 2024
Alexa Dringus

AMS's Senior Named Scholarship - Naval Weather Service Association
Roy Galang

NOAA William M. Lapenta Student Internship 2024
Jacob Widanski

Announced 2023

CIWRO Annual Awards

Award for Outstanding Publication
David Harrison
"For expertly and clearly crafting a WAF article documenting skillful calibrated, probabilistic thunderstorm guidance based on the HREF, which is the operational NWS standard for thunderstorm forecasting."

Outstanding Achievement in Research or Research Support – Joshua Martin
"Mr. Martin led an extraordinarily successful project of moving the experimental Warn-on-Forecast System to a more efficient cloud-based platform (cb-WoFS). Mr. Martins' technical expertise, dedication and leadership enabled him to reach the goal two months ahead of schedule, allowing cb_WoFS to support the NWS and 2022 Spring Forecasting Experiments."

Outstanding Achievement in Outreach, Education or Service
Patrick Skinner
"Dr. Patrick Skinner shares his extensive Warn-on-Forecast System expertise willingly, effectively, and repeatedly with the NWS. Tailoring presentations, facilitating testbeds, and guiding real-time operations chat rooms, he builds knowledgeable users. Often requested by Name, Dr. Skinner is a skillful ambassador whose service mindset advances the NOAA/CIWRO missions."

Outstanding Achievement in Outreach, Education or Service
Justin Sharpe
"Justin deserves this award for his tireless, innovative efforts to translate outcomes from VORTEX research to benefits for tornado-vulnerable populations. His clever ideas have created new capacities and made a difference in communities across the southeast."

CIWRO Director Award
Dale Morris
"For development of cloud-based Enhanced Weather Event Simulator training and assessments implemented at multiple NWS forecast offices in Southern and Central Regions."

NWS Awards

NWS Isaac Cline Award, Regional Level in the Category of Outreach
Jill Hardy, Alex Zwink, Andrew Wood, Dale Morris, Alyssa Woodward, Chris Spannagle, Jim LaDue, Alyssa Bates, Michael Lowe, Lexy Elizalde-Garcia, Melissa Lamkin, Ryan Pajelia, Katy Christian, Samantha Boyd, Raven Vasquez and Stephanie Edwards.
"For executing numerous outreach events that better communicate WDTD and NWS missions to the public, engage with the community using hands-on activities and encourage younger generations or meteorology students."

NWS Isaac Cline Award, Regional Level in the Category of Meteorology
Jim LaDue, Chris Spannagle, Kevin Grempler, Jill Hardy, Katy Christian, Christina Crowe, and Barb Mayes Boustead.
"For collaborating across OCLO divisions and creating the Post-Storm Damage Surveying training series."

NWS Isaac Cline Award, Regional Level in the Category of Hydrometeorology
Mike Magsig, Katy Christian, Jill Hardy, Dave Creveling, Melissa Lamkin, Jake Sorber and Dale Morris
"For implementing Hazard Services capabilities in the Radar & Applications Course, providing a more operationally accurate training experience for forecasters in the course in the new era of warning operations."

Student Awards

First Place Undergraduate Student Presentation at National Weather Association Annual Meeting “Advancing Risk Communication through a National Survey of U.S. Spanish Speakers”
Vanessa Dunham

First Place Graduate Student Presentation “Probabilistic Information: Is it Useful for Bilingual Speakers?”
Joseph Trujillo-Falcón

Second Place OU GIS Day Poster Competition “The Keeper Movement and Water Policy”
Adeline Miller

Outstanding Oral Presentation at AMS WAF/NWP Conference “Producing Machine Learning-Based Severe Weather Guidance at Watch-to-Warning Lead Times”
Sam Varga

Outstanding Oral Presentation at AMS WAF/NWP Conference “Verification of Quasi-Linear Convective Systems Predicted by the WoFS”
Kelsey Britt

Second place Outstanding Student Presentation Award for “Examining the Impact of Mid-level Shear and Low-Level Storm-Relative Flow on Supercell Characteristics and Evolution”
Andrew MuehrSecond Place Poster Presentation “QLCS Tornado Detection using Merged Products derived from MRMS”
Tyler Pardun

Third Place Oral Presentation at AMS Annual Meeting “Considerations for CopterSonde Use in NWS Operational Forecasting”
Connor Bruce

Second Place Oral Presentation at AMS 22nd Conf. on Artificial Intelligence for Environmental Science
Bethany Earnest

Second Place Award for AMS Societal Applications: Policy, Research and Practice student presentations
Sean Ernst

Outstanding Student Oral Presentation at 32nd Conference on Weather Analysis and Forecasting
Madeline Diedrichsen

OU College of Atmospheric & Geographic Sciences Outstanding Senior First Alternate 2022-2023

Undergraduate Academic Achievement Award – Meteorology Senior with the Best Overall GPA 2022-2023
OU Campus Awards - Letzeiser Honor List 2023
OU Campus Awards - Campus Life Award 2023
Marcus Ake

NOAA Ernest F. Hollings Undergraduate Scholarship 2024
Roy Galang

Fawbush–Miller Endowed Scholarship 2022-2023
Jacob Widanski

Very Early Career Outstanding Presentation Award at AMS Meso/WAF/NWP, "Impacts of Low-Level Shear Orientation and Magnitude on Structure and Mesovortex Production in Idealized Squall Lines"
Matthew Brown

Richard J. Doviak Award
Lauren Pounds

Announced 2022

Student Awards

Kelvin & Lisa Droegemeier Scholarship for Excellence in Meteorology 2021-2022
Undergraduate Academic Achievement Award – Meteorology Junior with the Best Overall GPA 2021-2022
OU College of Arts and Sciences Department of Mathematics Frederick B. Swan Scholarship
Marcus Ake

Announced 2021

Student Awards

NOAA Ernest F. Hollings Undergraduate Scholarship 2022
Marcus Ake

APPENDIX F: TASK II PROPOSALS

1. WDTD
2. Operationally Relevant Severe Weather Forecasting Research (SPC)
3. IDSS/OPG Support for the NWS Training Center/Operations Proving Ground
4. VORTEX-Observations (NSSL Project 2)
5. Forecasting a Continuum of Environmental Threats (FACETs) (NSSL Project 4)
6. Societal Applications Research (Social Science) (NSSL Project 7)
7. Warning Research – General warning research and operational system activities (WRDD Other) (NSSL Project 12)
8. Advances in improving radar data quality for the purpose of improving forecasting and flood/flashflood warning guidance for forecasters (Hydro) (NSSL Project 5)
9. Testing and implementing data sets, applications, and web visualization tools into an operational MRMS (NSSL Project 6)
10. WRDD – Severe Weather Applications (Severe Apps) (NSSL Project 9)
11. HWT Operations and Support (HWT) (NSSL Project 11)
12. Advances in dual-polarization weather radar and observations (Dual-Pol) (NSSL Project 13)
13. Development and evaluation of new algorithms and techniques for use by the Radar Operations Center (NSSL Tech Transfer)
14. Advances in Warn-On-Forecast (WoF) Research and Development (NSSL Project 1)
15. Tornado Warning Improvement and Extension Program (TWIEP) (VORTEX Science) (NSSL Project 8)
16. Advances in phased-array weather radar and observations (PAR) (NSSL Project 14)
17. Other Advances in Forecast Research and Development (FRDD Other) (NSSL Project 3)
18. Prototype development and evaluation of new science and signal processing techniques to address operational problems and emerging requirements for the WSR-88D (NSSL RPI)
19. Improving surface layer and boundary layer parameterizations in Numerical Weather Prediction Models through targeted observations and numerical simulations (ARL/ATDD) (NSSL Project 16)
20. Other advances in remote-sensing systems and observations (NSSL RRDD Other)
21. Advances in understanding the impacts of severe and high-impact weather on transportation safety (Transportatoin) (NSSL Project 10)
22. Analysis of weather radar observations of severe convective storms to understand severe storm processes and improve warning decision support (ROC Student Support)

APPENDIX G: DIRECT TO CI FUNDING

Sponsor	**Project Title**
Amateur Radio Digital Communications	Equipment Upgrade and Technical Refresh for the Alpha Sigma Delta Amateur Radio Society of OU
Argonne National Laboratory	Data Quality Manager for the ARM Program
Australian Bureau of Meteorology	Development of Multistatic Passive Radar Networks for S-Band Weather Radars
Battelle - Pacific Northwest National Laboratory	Data Quality Manager for the ARM Program
Columbia University	Development of Global Flash Flood Threat Forecasting Tools for NASA GEO Project: Towards A Global Flood & Flash Flood Early Warning Early Action System Driven by NASA Earth Observations and Hydrologic Models
Jet Propulsion Laboratory, California Institute of Technology	Analysis of the performance of the Atmospheric Infrared Sounder (AIRS) retrieval system
NASA - Goddard Space Flight Center	Investigation of Microphysics and Precipitation for Atlantic Coastal Threatening Snowstorms (IMPACTS)
NASA - Headquarters	Quantification of Error Characteristics of NASA's Tropical Rainfall Measuring Mission and Global Precipitation Measurement Mission Products
NASA - Headquarters	Bridging the Global Precipitation Measurement (GPM) Level II and Level III Precipitation Multi-Radar/Multi-Sensor-GPM (MRMS-GPM)
NASA - Headquarters	Evaluation of Surface Precipitation Products from NASA's Tropical Rainfall Measuring Mission and Global Precipitation Measurement Mission
NASA - Headquarters	OU contributions to AOS algorithm development, suborbital activities and science transition planning
National Center for Atmospheric Research	From Clouds to Precipitation: Multiscale Dynamics-Microphysics Interactions in Cumulus Clouds
National Science Foundation	Understanding the Relationship Between Tornadoes and Debris Through Observed and Simulated Radar Data
National Science Foundation	Collaborative Research: Targeted Observation by Radars and UAS of Supercells
National Science Foundation	Investigating the impact of ambient deep-tropospheric vertical wind shear on tornadoes and their attendant supercells within tropical cyclones
National Science Foundation	Collaborative Research: Experiment of Sea Breeze Convection, Aerosols, Precipitation and Environment (ESCAPE)

National Science Foundation	RAPID: Collaborative Research: Multi-Scale Investigation into the Storm Processes of the 10 August 2020 Midwest Derecho
National Science Foundation	Collaborative Proposal: The QBO-MJO Connection: Positive Feedbacks from Extratropical Wave Forcing
National Science Foundation	Enhancing Communities Preparedness and Resilience to Post-Wildfire Hydrology in Mountainous Areas
National Science Foundation	Observational and Numerical Modeling Study of Downburst Generation Using Dual-Polarization Radar
National Science Foundation	Hybrid Ensemble Variational Analysis of Polarimetric Radar Data to Improve Microphysi-cal Parameterization and Short-term Weather Prediction
National Science Foundation	Collaborative research: Improving our understanding of supercell storms from convection initiation to tornadogenesis via innovative observations, numerical simulations, and analysis techniques
National Science Foundation	Collaborative Research: Project LEE: Lake-Effect Electrification and the impacts of wind turbines on electrification east of Lake Ontario
National Science Foundation	Collaborative Research: EAGER: Initial Evaluation of Polarimetric Phased Array Radar for the Study of Storm Electrification and Lightning
National Science Foundation	Cloud-aerosol-dynamic interactions in Cold Air Outbreaks over the Arctic Ocean
National Science Foundation	Understanding the Internal Structure and Near-Storm Environments of Supercells via Innovative Analysis of TORUS Observations
National Science Foundation	Collaborative Research: Using polarimetric radar observations, cloud modeling, and in situ aircraft measurements for large hail detection and warning of impending hail
National Science Foundation	How does the extratropical transition of tropical cyclones impact tornadoes and supercells?
National Science Foundation	Collaborative Research: AGS-FIRP Track 3: In-situ Collaborative Experiment for the Collection of Hail In the Plains (ICECHIP)
National Science Foundation	Collaborative Research: Planning: CRISES: Human-Centered Early Warning Systems for Weather Hazards.
Oklahoma State University	Real-time Weather Awareness for Enhanced UTM Safety Assurance
Sandia Laboratories	Building Readiness and Resilience in U.S. Food, Agriculture, and Veterinary Systems
Sandia Laboratories	Novel Lightning Monitoring for Wildfire Risk - Analysis and Field Support

State of Missouri, Department of Transportation	Creation of a rapidly-updating Road Weather Impacts Prediction System (RWIPS)
State of Oklahoma, Department of Commerce	Oklahoma State Energy Security Plan
State of Oklahoma, Regents for Higher Education	Five Nights of Eddies | Meteorology Afterschool RFP
Texas Tech University	Employing a combined observation and simulation-based framework to investigate spatiotemporal variability in urban heat and associated heat advection
U.S. Department of Defense, Office of Naval Research	Advance the Cutting-Edge Science and Technology in Radar and Satellite Data Assimilation for Analyses and Predictions of Severe Storms and Tropical Cyclones
U.S. Department of Energy	High concentrations of ice: investigations using polarimetric radar observations combined with in situ measurements and cloud modeling
U.S. Department of Energy	Use of MARCUS, MICRE and COMBLE data to enhance understanding of cloud and aerosol processes in their interactions in high-latitude regions
U.S. Department of Energy	Coastal Urban Boundary-layer Interactions with Convection (CUBIC)
U.S. Department of Energy	Surface, aerosol, and meteorological controls on Arctic boundary layer clouds: Observations andsimulations from MOSAiC and COMBLE
U.S. Department of Energy	Surface, Aerosol, and Meteorological Controls on Subtropical Coastal Metropolitan Convective Clouds: Observations and Simulations from TRACER
U.S. Department of Energy	Impacts of cloud-aerosol-meteorology relations in mixed-phase clouds on radiative fluxes over high Latitudes
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	A Weather-Ready Nation Para Todos: Evaluating Current Practices in Communicating Hazardous Weather Risks to Spanish Speakers
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Achieving Greater Tornado Resilience through Informed Decision-Making about Reinforcing the Anchorage of Mobile and Manufactured Homes
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Analysis and OSEs of UAS observations for improved high-impact weather forecasts
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	BIL ACME/SHMET Weather Proposal
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	BIL Probabilistic Fire Weather Guidance
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Bridging Watch-to-Warning Forecast Operations with Refined Probabilistic Guidance

U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	CIWRO/NSSL IRA Hail Climatology Development Proposal
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Creating a probabilistic, ensemble-based approach to winter precipitation type for the National Blend of Models with the Spectral Bin Classifier
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Creation and production of a CONUS-wide gridded analysis-of-record for ice accumulation
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Developing enhanced diagnostic output for the UFS: Increasing information extraction with minimal expense
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Developing the Next-Generation Winter Weather Experiment Testbed: Integrating Road
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Development of Real-Time Multistatic Passive Radar Networks for Severe Weather Prediction
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Direct Assimilation of GOES-R Geostationary Lightning Mapper (GLM) Data within JEDI Hybrid System for Operational UFS Convection-Allowing Predictions
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	DRSA Fire Weather
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	DRSA Fire Weather Testbed
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Enhancing the SPC's Convective Outlook with Continuous Probabilities and Conditional Intensity Forecasts
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Ensemble Sensitivity Analysis to Investigate Mesoscale Heterogeneity in Southeast US Tornado Events
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Examining Regional Differences in Attitudes and Tendencies for Protective Action Decisions
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Examining the environmental relationships and processes influencing tornado behavior in the Southeast United States
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Fire weather observations analysis
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Improving and Expanding Gridded Snowfall Analyses and Seasonal-to-Subseasonal Snowfall Forecasts
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Improving Quality Control of Multi-Radar Multi-Sensor Products from Non-Meteorological Radar Data Artifacts
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Improving the Effectiveness of IDSS For Severe Convective Weather and Flood Events
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Integration of a road temperature analysis and forecast into NWS operations

U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Probabilistic Prediction of Thunderstorm Hazards using the NOAA Warn-on-Forecast System and Machine Learning
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Products to Guide Impact-Based Flash Flood Warnings in the National Weather Service
U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration	Venturing into the Vertical: Optimizing Boundary Layer Profiling in Mesonets
University of Colorado	Measurements of TRACER Pre-Convective Conditions and Mesoscale Circulations Using Small Unmanned Aircraft Systems (sUAS)

APPENDIX H: EXECUTIVE BOARD

The CIWRO Director benefits from regular input from the CIWRO Executive Board. The Executive Board meets once or twice a year to provide recommendations to the Director about management and budgetary issues. The CIWRO Director relies on their advice when making decisions affecting activities within CIWRO. The CIWRO Executive Board is comprised of the following individuals: the Director of CIWRO; three members designated by the OU Provost; two members designated by the Director of OAR; two members designated by the Director of NWS; two members elected by the CIWRO Council of Fellows; Director of SoM; Director of NSSL; Director of SPC; Director of ROC; Director of WDTD; Director of Norman NWSFO; Director of NWSTC; and Dean of AGS. In addition, the Director of ARL/ATDD, Director of OPG, Chief of the NWS Leadership Academy, and a representative from each of our consortium partners (HU, PSU, AU, and TTU) serve on the Board. The current composition of the board is listed below:

- Director of CISHIWRO, Chair (G. McFarquhar)
- Three members designated by OU Provost (R. Palmer, R. McPherson, C. Silva)
- Two Members designated by Director of OAR (K. Hondl, P. Heinselman)
- Two Members designated by NWS Director (P. Marsh, D. Rinderknecht)
- Two Members elected by CISHIWRO Council of Fellows (B. Cheong, M. Xue)
- Director of SoM, ex officio (C. Homeyer)
- Director of NSSL, ex officio (D. Carlis)
- Director of SPC, ex officio (R. Schneider)
- Director of ROC, ex officio (T. Clark)
- Director of WDTD, ex officio (E. Mahoney)
- Director of Norman NWSFO, ex officio (M. Fox)
- Director of OCLO, ex officio (J. Ogren)
- Director of ARL/ATDD, ex officio (J. Kochendorfer)
- Representative from Howard University (T. Adams-Fuller)
- Representative from Penn State University (P. Markowski)
- Representative from Texas Tech University (C. Weiss)
- Representative from University at Albany (C. Thorncroft)
- Acting Dean, AGS, ex officio (P. Klein)

APPENDIX I: LIST OF CIWRO FELLOWS

- Dr. Kodi Berry, FACETs Program Lead, NSSL
- Dr. Michael I. Biggerstaff, Professor, School of Meteorology (SoM)
- Dr. Howard B. Bluestein, Professor Emeritus, SoM
- Dr. David Bodine, Associate Professor, SoM
- Dr. Keith Brewster, Senior Research Scientist and Director of Operations, Center for Analysis and Prediction of Storms (CAPS)
- Dr. Harold E. Brooks, Research Meteorologist, NSSL
- Dr. Kristin Calhoun, Research Scientist, NSSL
- Dr. DaNa L. Carlis, Director, NSSL
- Dr. Frederick H. Carr, Professor Emeritus of Meteorology
- Dr. Boonleng Cheong, Research Scientist, Advanced Radar Research Center (ARRC)
- Dr. Vanna Chmielewski, Research Meteorologist, NSSL
- Dr. Adam Clark, Research Meteorologist, NSSL
- Dr. Race Clark, Meteorologist, NSSL
- Mr. Terrance Clark, Director, NOAA Radar Operations Center (ROC)
- Dr. Michael Coniglio, Research Meteorologist, NSSL
- Dr. Chris Fiebrich, Executive Director, Oklahoma Mesonet and Associate Director (OCS)
- Mr. Mark Fox, Meteorologist in Charge, NWS Forecast Office, Norman
- Dr. Caleb Fulton, Associate Professor, School of Electrical and Computer Engineering (ECE)
- Dr. Jason Furtado, Associate Professor, SoM
- Dr. Thomas Galarneau, Research Physical Scientist, NSSL
- Dr. Jidong Gao, Research Scientist, NSSL
- Dr. Jeremy Gibbs, Research Meteorologist, NSSL
- Dr. J.J. Gourley, Research Hydrologist, NSSL
- Dr. Scott Greene, Chair and Professor, Department of Geography and Environmental Sustainability (DGES)
- Dr. Pamela Heinselman, Division Chief, Forecast Research & Development Division, NSSL
- Mr. Kurt Hondl, Deputy Director, NSSL
- Dr. Yang Hong, Professor, CEES
- Mr. Ken Howard, Meteorologist, NSSL
- Dr. Xiaoming Hu, Senior Research Scientist, CAPS
- Dr. Hank Jenkins-Smith, Professor, Department of Political Science and Director, National Institute for Risk and Resilience (NIRR)
- Dr. Israel Jirak, Science and Operations Officer, NOAA SPC
- Dr. Pierre Kirstetter, Associate Professor, CEES/SoM
- Dr. Petra Klein, Executive Associate Dean, College of Atmospheric & Geographic Sciences, E.K. Gaylord Presidential Professor and Associate Professor, SoM
- Dr. Kevin Kloesel, Director, (OCS) and Associate Professor, SoM
- Dr. Fanyou Kong, Senior Research Scientist, CAPS
- Dr. Daphne LaDue, Senior Research Scientist, CAPS
- Dr. Chengsi Liu, Senior Research Scientist, CAPS
- Mr. Ed Mahoney, Chief, NOAA WDTD

- Dr. Edward Mansell, Research Scientist, NSSL
- Dr. Patrick Marsh, Chief, Science Support Branch, SPC
- Dr. Kimberly Klockow McClain
- Dr. Amy McGovern, Professor, School of Computer Science and SoM
- Dr. Renee McPherson, University Director, SC-CASC and Associate Professor, DGES
- Mr. Richard Murnan, Radar Meteorologist, ROC
- Dr. LaToya Myles, Deputy Director, Atmospheric Turbulence & Diffusion Division, NOAA Air Resources Laboratory
- Mr. John Ogren, Chief Learning Officer, NOAA
- Dr. Robert D. Palmer, Associate Vice President for Research & Partnerships, Executive Director, Advanced Radar Research Center, Tommy Craighead Chair and Professor, SoM
- Dr. David Parsons, Professor Emeritus, SoM
- Dr. Corey Potvin, Research Meteorologist, NSSL
- Dr. Erik Rasmussen, Research Meteorologist, NSSL
- Dr. Jens Redemann, Professor, SoM
- Dr. Anthony Reinhart, Research Meteorologist, NSSL
- Dr. Joseph Ripberger, Associate Professor, Political Science and Associate Director and Deputy Director for Research, IPPRA
- Dr. Naoko Sakaeda, Associate Professor, SoM
- Dr. Jorge Salazar-Cerreño, Assistant Professor, ECE
- Dr. Russell Schneider, Director, SPC
- Dr. Mark Shafer, Associate State Climatologist, OCS; Director, SCIPP; Assistant Professor, DGES
- Dr. Hjalti Sigmarsson, Associate Professor, ECE
- Dr. Carol Silva, Edith Kinney Gaylord Presidential Professor, Department of Political Science, co-Director, IPPRA
- Dr. Elizabeth Smith, Research Meteorologist, NSSL
- Dr. Nathan Snook, Senior Research Scientist and Director of Research, CAPS
- Dr. Jeff Snyder, Meteorologist, NSSL
- Dr. Chris Thorncroft, Director, Atmospheric Sciences Research Center, University of Albany
- Dr. Xuguang Wang, Robert Lowry Chair Professor, Presidential Research Professor, SoM
- Mr. Danny Wasielewski, Radar Engineer, NSSL
- Dr. Sean Waugh, Instrumentation Meteorologist, NSSL
- Dr. Chris Weiss, Professor, Atmospheric Sciences, Texas Tech University
- Dr. Louis J. Wicker, Chief Scientist, Warn on Forecast - NSSL
- Dr. Qin Xu, Research Meteorologist, Models and Assimilation Team, NSSL
- Dr. Ming Xue, Director, CAPS; Weathernews; George Lynn Cross Research Professor, SoM
- Dr. Mark Yeary, Presidential Professor, ECE
- Dr. Tian-You Yu, Professor, ECE and Director of Operations, ARRC
- Dr. Guifu Zhang, Professor, SoM
- Dr. Jian Zhang, Research Meteorologist, NSSL
- Dr. Yan Zhang, Professor, ECE
- Dr. Conrad Ziegler, Research Meteorologist, Models and Assimilation Team, NSSL
- Dr. Dusan S. Zrnic, Senior Engineer and Group Leader, Doppler Radar and Remote Sensing Research Group, NSSL