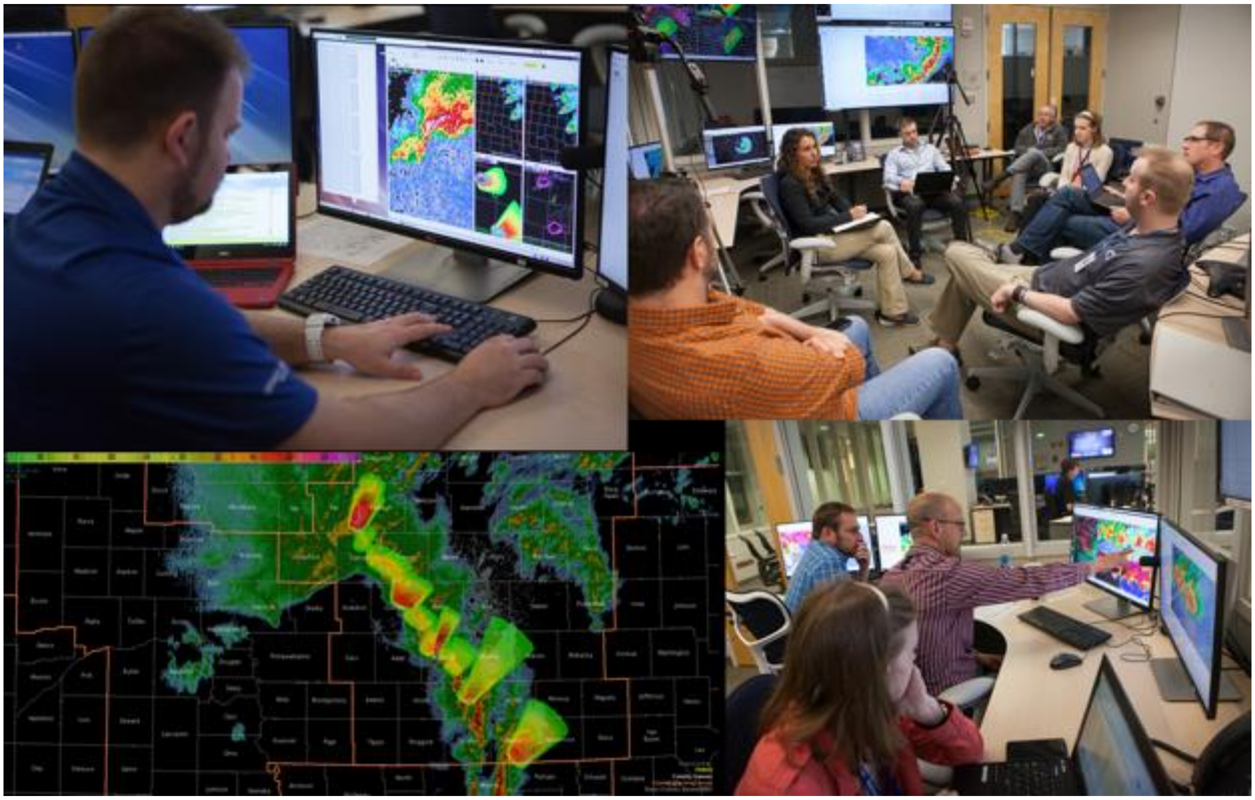

Cooperative Institute for Mesoscale Meteorological Studies

Annual Report

Prepared for the
National Oceanic and Atmospheric Administration
Office of Oceanic and Atmospheric Research

Cooperative Agreement NA16OAR4320115

Fiscal Year – 2017

Cover image – *Images from the Hazard Services – Probabilistic Hazard Information (HS-PHI) 2017 spring experiment in the NOAA Hazardous Weather Testbed, including various forecaster and researcher interactions with the software and during group discussions. Also shown is a screen capture of the HS-PHI application, showing probabilistic tornado "plumes" for a Quasi-Linear Convective System (QLCS). For more on this project, "Hazard Services – Probabilistic Hazard Information (HS-PHI)", involving Greg Stumpf (CIMMS at OST/MDL/DAB) and Tiffany Meyers (CIMMS at NSSL), see pages 143-145.*

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COOPERATIVE INSTITUTE FOR MESOSCALE METEOROLOGICAL STUDIES
THE UNIVERSITY OF OKLAHOMA

Annual Report of Research Progress Under
Cooperative Agreement NA16OAR4320115
During the 2017 Fiscal Year: July 1, 2016-June 30, 2017

Randy A. Peppler, Interim Director
Tracy L. Reinke, Executive Director of Finance and Operations
Sebastian Torres, Assistant Director for NOAA Relations

INTRODUCTION

General Description of CIMMS and its Core Activities

The Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) was established in 1978 as a cooperative program between the National Oceanic and Atmospheric Administration (NOAA) and The University of Oklahoma (OU). CIMMS provides a mechanism to link the scientific and technical resources of OU and NOAA to create a center of research excellence in weather radar, stormscale meteorological phenomena, regional climate variations, and related subject areas – all with the goal of helping to produce better forecasts and warnings that save lives and protect property.

CIMMS promotes cooperation and collaboration on problems of mutual interest among university researchers and the NOAA Office of Oceanic and Atmospheric Research (OAR) National Severe Storms Laboratory (NSSL), National Weather Service (NWS) Radar Operations Center (ROC) for the WSR-88D (NEXRAD) Program, NWS NCEP (National Centers for Environmental Prediction) Storm Prediction Center (SPC), NWS Warning Decision Training Division (WDTD), NWS Norman Forecast Office (OUN), NWS Training Center (NWSTC) in Kansas City, Missouri, and NOAA Air Resources Laboratory Atmospheric Turbulence and Diffusion Division (ATDD) in Oak Ridge, Tennessee.

CIMMS research contributes to the NOAA mission through improvement of the observation, analysis, understanding, and prediction of weather elements and systems and climate anomalies ranging in size from cloud nuclei to multi-state areas. Advances in observational and analytical techniques lead to improvements in understanding of the evolution and structure of these phenomena. Understanding provides the foundation for more accurate prediction of hazardous weather and anomalous regional climate. Better prediction contributes to improved social and economic welfare. Because small-, meso-, and regional-scale phenomena are also important causes and manifestations of climate, CIMMS research is contributing to improved understanding of the global climate system and regional climate variability and change. CIMMS promotes research collaboration between scientists at OU and NOAA by providing a center where government and academic scientists may work together to learn about and apply their knowledge of stormscale weather and regional-scale climate processes.

CIMMS is part of the National Weather Center, a unique confederation of federal, state, and OU organizations that work together in partnership to improve understanding of the Earth's atmosphere. Recognized for its collective expertise in severe weather, many of the research and development activities of the Center have served society by improving weather observing and forecasting, and thus have contributed to reductions in loss of life and property.

In addition to CIMMS, National Weather Center organizations include:

- NOAA OAR National Severe Storms Laboratory (NSSL)
- NOAA NWS Warning Decision Training Division (WDTD)
- NOAA NWS NCEP Storm Prediction Center (SPC)
- NOAA NWS Radar Operations Center (ROC)
- NOAA NWS Norman Forecast Office (OUN)
- Oklahoma Climatological Survey (OCS)
- OU Center for Analysis and Prediction of Storms (CAPS)
- OU Advanced Radar Research Center (ARRC)
- OU College of Atmospheric and Geographic Sciences
- OU School of Meteorology
- OU Department of Geography and Environmental Sustainability

CIMMS concentrates its research and outreach efforts and resources on the following principal themes: (1) weather radar research and development, (2) stormscale and mesoscale modeling research and development, (3) forecast and warning improvements research and development, (4) impacts of climate change related to extreme weather events, and (5) societal and socioeconomic impacts of high impact weather systems.

This report describes NOAA-funded research and outreach progress made by CIMMS scientists at OU and those assigned to our collaborating NOAA units under cooperative agreement NA16OAR4320115 during 1 July 2016 through 30 June 2017. Publications written, awards received, and employee and funding statistics are presented in Appendices.

Management of CIMMS, including Mission and Vision Statements, and Organizational Structure

An Executive Board and Council of Fellows help advise CIMMS.

The CIMMS Executive Board is to meet quarterly to provide advice and recommendations to the Director of CIMMS regarding appointments, procedures, and policies; to review and adopt bylaws; and to periodically review the accomplishments and progress of the technical and scientific programs and projects of the CIMMS.

The Council of Fellows meets as needed and is composed of a cross-section of local and national scientists who have expertise relevant to the research themes of CIMMS and are actively involved in the programs and projects of CIMMS. Appointment as a Fellow, by the CIMMS Executive Board, is normally for a two-year term, and reappointment is possible. Appointments may be made for a shorter period of time or on a part-time basis with the concurrence of the appointee and the CIMMS Executive Board. Fellows will review and suggest modifications of bylaws, participate in reviews of CIMMS activities, and elect two of their number to serve on the Executive Board. The Executive Board appoints Fellows.

The Mission and Vision Statements of CIMMS are as follows:

Mission – *To promote collaborative research among University and NOAA scientists on problems of mutual interest to improve basic understanding and to help produce better forecasts and warnings that save lives and property*

Vision – *A center of research excellence in mesoscale meteorology and related topics, fostering vibrant University-NOAA collaborations*

The organizational structure of CIMMS in FY17 included: Interim Director (Randy Peppler), Executive Director of Finance and Operations Director (Tracy Reinke), Assistant Director for NOAA Relations (Sebastian Torres), Account and Budget Representative (Jamie Foucher), and Staff Assistant (Tanya Riley). Scientists, students, and post-docs are housed on the OU campus in its National Weather Center (NWC), at the NWSTC in Kansas City, and at ATDD in Oak Ridge. Some CIMMS undergraduate students have duty stations off-campus at ROC in Norman.

Executive Summary Listing of Activities during FY2017

Theme 1 – Weather Radar Research and Development

At the very center of NOAA's mission are the objectives of achieving a "reduced loss of life, property, and disruption from high-impact weather events", "improved transportation efficiency and safety", and "improved freshwater resource management" (*NOAA' s Next Generation Strategic Plan,* Long-Term Goal: Weather Ready Nation, pp. 10-14*,* December 2010). The weather systems involved include severe thunderstorms, tornadoes, tropical storms and hurricanes, and winter cyclones. Those systems produce the high intensity precipitation, strong winds, flooding, lightning strikes, freezing rain, and large snow accumulations that damage property, cost lives, disrupt transportation, and cause other economic dislocation. Reduction of these adverse impacts can result from the availability and use of accurate forecasts of the above weather systems and their associated phenomena, for future periods ranging from several days down to a few minutes. One of the essential starting points for developing those forecasts is the detailed observation of the present state of the atmosphere.

For almost 60 years, remote sensing via weather radar has been a vital source of the necessary observations. The present national weather radar system (WSR-88D) uses reflectivity and Doppler velocity measurements to document the location and movement of the above weather systems, and indicate the time evolution of their precipitation intensity and wind strength. However, this radar system soon will be as old (30 years) as the chronologically and technologically ancient system (WSR-57) that it replaced in 1988. This situation has two crucial implications for NOAA's continued pursuit of its above objectives to achieve a "reduced loss of life, property, and disruption from high impact weather events", "improved transportation efficiency and safety", and "improved freshwater management". First, NOAA and its partners must complete the recently initiated development of the new Multi-Function Phased Array Radar (MPAR) system that will replace the WSR-88D and is incorporating all relevant technological advances during the last 20+ years. Second, since completion of this development activity will require another 7-12 years at its current rate of progression, the ongoing current WSR-88D upgrades (especially Dual-Polarization) must be brought to fruition as soon as possible.

During the past year, research was conducted on:

- ***NSSL Project 2 – Hydrometeorology Research***

- ***CIMMS Task III Projects***
    - ARRC Demonstrator Development Activities for the MPAR Program: CPPAR and HORUS

Theme 2 – Stormscale and Mesoscale Modeling Research and Development

Research and development for stormscale and mesoscale modeling are essential for NOAA's aforementioned objectives. Use of stormscale and mesoscale models is a major ingredient of the forecasting and nowcasting procedures for high impact weather events, and is expected to grow in the future. The initialization of those prediction models is depending increasingly on wind and other observations from the current weather radar systems. This dependence also is anticipated to expand and therefore is a principal motivation for the weather radar research and development proposed above -- to improve the initialization and hence performance of the prediction models. At the center of this radar-modeling interface is the manner in which radar data are ingested into the models, especially in combination with measurements from other platforms (e.g., satellite, rawinsonde, surface) via "assimilation" procedures. In addition to their predictive roles, stormscale and mesoscale models also are used extensively in a research mode to understand better the behavior of weather systems on those scales. The atmospheric processes that receive particular attention in these simulations include mesoscale dynamics, convective initiation, cloud dynamics and microphysics, and the precipitation process. Also investigated is the sensitivity of the simulation results to the data assimilation procedures. The ultimate goal of such stormscale and mesoscale simulation research is to improve the performance of the operational forecasting models.

During the past year, research was conducted on:

- ***NSSL Project 3 – Numerical Modeling and Data Assimilation***

- ***NSSL Project 4 – Hydrologic Modeling Research***

- ***CIMMS Task III Projects***
    - Using Total Lightning Data from GLM/GOES-R to Improve Real-Time Tropical Cyclone Genesis and Intensity Forecasts
    - Ensemble Kalman Filter and Hybrid Data Assimilation for Convective-Scale "Warn-on Forecast"

Theme 3 – Forecast and Warning Improvements Research and Development

It is under this theme that the results of the research and development from the two preceding themes are integrated and converted into improved weather forecasts and warnings disseminated to the U.S. public. The ultimate outcome is to provide NWS forecasters routinely with enhanced information on which to base their forecasts. Two areas of highly innovative activity, anchored within the Hazardous Weather Testbed (HWT), dominate this effort – the Experimental Forecasting Program and the Experimental Warning Program. Activity within this theme also is dominated by the training activities of CIMMS scientists at the Warning Decision Training Branch.

During the past year, research and training were conducted on:

- ***NSSL Project 6 – Development of Technologies and Techniques in Support of Warnings***

- ***ROC Project 10 – Analysis of Dual Polarized Weather Radar Observations of Severe Convective Storms to Understand Severe Storm Processes and Improve Warning Decision Support***

- ***WDTD Project 12 – Warning Decision-Making Research and Training***

- ***OST Project 13 – Research on Integration and Use of Multi-Sensor Information for Severe Weather Warning Operations***

- ***ARL Project 15 – Weather and Climate Change Monitoring and Research Support of the Atmospheric Turbulence and Diffusion Division of NOAA's Air Resources Laboratory***

- ***CIMMS Task III Projects***
    - Contribution to Model Development and Enhancement Research Team by the Center for Analysis and Prediction of Storms

- Advanced Data Assimilation and Prediction Research for Convective-Scale “Warn-on-Forecast”
- Mobile Radar Operations to Support VORTEX-SE
- Three-Dimensional Profiling of the Severe Weather Environment

Theme 4 – Impacts of Climate Change Related to Extreme Weather Events

Here, we are concerned with the regional and global climate system context of mesoscale and stormscale weather variability, and especially the functioning of what now is termed the weather-climate interface. The genesis and trends of extreme events are of particular interest, given society’s current concerns about climate maintenance and change. The optimum path forward will require an appropriate combination of observational (using fine resolution data) and modeling (emphasizing convection) research. This theme also addresses the NOAA objective of achieving “improved scientific understanding of the changing climate system and its impacts” and “assessments of current and future states of the climate system that identify potential impacts and inform science, services, and stewardship decisions” (*NOAA’s Next Generation Strategic Plan*, Long-Term Goal: Climate Adaptation and Mitigation, pp. 5-10, December 2010).

During the past year, no research and outreach were conducted within this theme on the new cooperative agreement.

Theme 5 – Societal and Socioeconomic Impacts of High Impact Weather Systems

This theme contributes to several of NOAA’s objectives - - providing “mitigation and adaptation choices supported by sustained, reliable, and timely climate services”; achieving “a climate-literate public that understands its vulnerabilities to a changing climate and makes informed decisions”; and furnishing “services meeting the evolving demands of regional stakeholders” (*NOAA’s Next-Generation Strategic Plan,* Long-Term Goal: Climate Adaptation and Mitigation, pp. 5-10, December 2010). Much of the effort here is motivated and fed by results obtained under the Forecast and Warning Improvements and Extreme Weather-Climate Change Impacts themes that, in turn, are built around the core of the more basic Weather Radar and Stormscale/Mesoscale Modeling Research and Development. The goal here is to facilitate the mitigation (enhancement) of the adverse (beneficial) social and socioeconomic impacts of high-impact weather systems and regional/seasonal-scale climate variations. Thus, our contributions to this theme are part of NOAA’s crucial ultimate interface with society, and therefore will reflect the continuing and increasing involvement of OU social scientists.

During the past year, research and outreach were conducted on:

- ***NSSL Project 9 – Evaluating the Impact of New Technologies, Data, and Information in the Operational Forecasting Environment***

- ***CIMMS Task III Projects***
    - Coping with Drought: Building Resilience to Drought
    - Establishing a Baseline: Public Reception, Understanding, and Responses to Severe Weather Forecasts and Warnings in the Contiguous United States

Public Affairs and Outreach

CIMMS education and outreach activities help NOAA achieve its objectives of providing "an engaged and educated public with an improved capacity to make scientifically informed environmental decisions" and making "full and effective use of international partnerships and policy leadership to achieve NOAA's mission objectives" (*NOAA's Next Generation Strategic Plan*, Engagement Enterprise Objective, pp. 30-32, December 2010). CIMMS location and role within the OU-NOAA National Weather Center (NWC) has embedded it within a wide-ranging and ongoing set of education and outreach activities that will draw continuously on the knowledge developed within the five above research themes. Those activities (a) involve local and national outreach to the general public, (b) extend across all levels of formal education, and (c) provide post-doctoral and professional development opportunities for individuals in careers related to the atmospheric sciences.

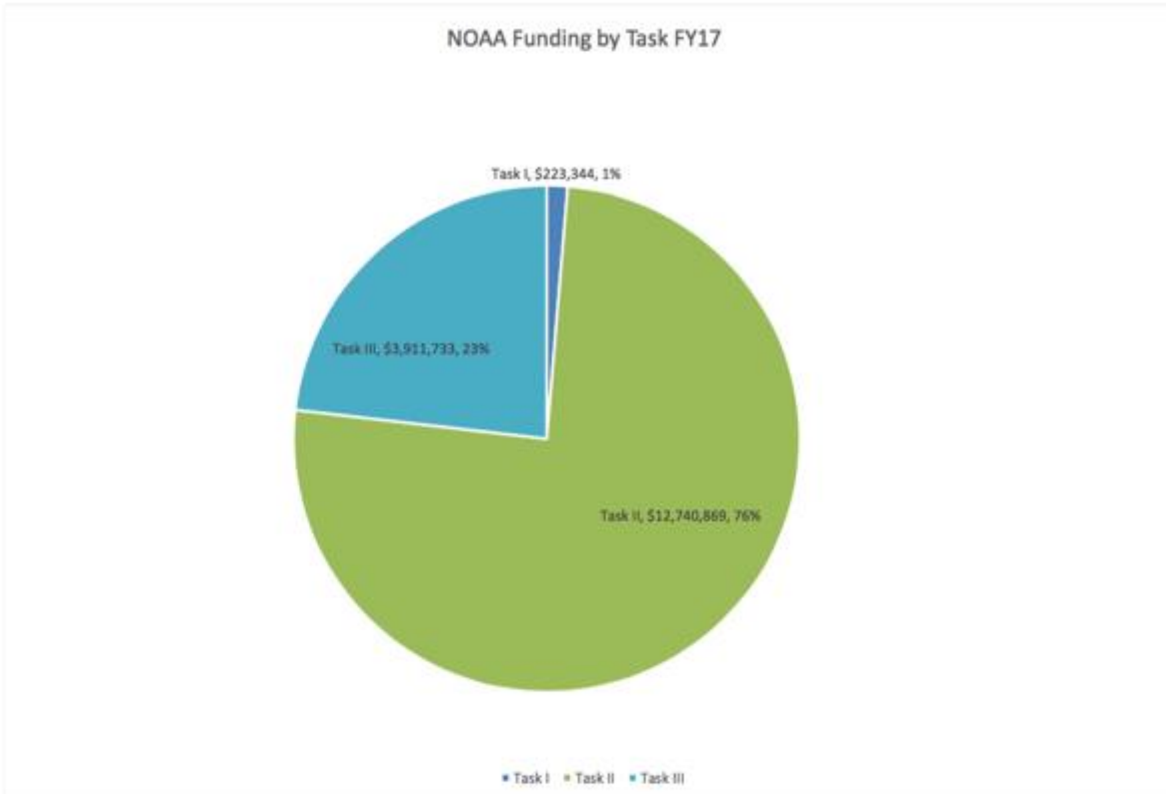
During the past year, public affairs and outreach activities included:

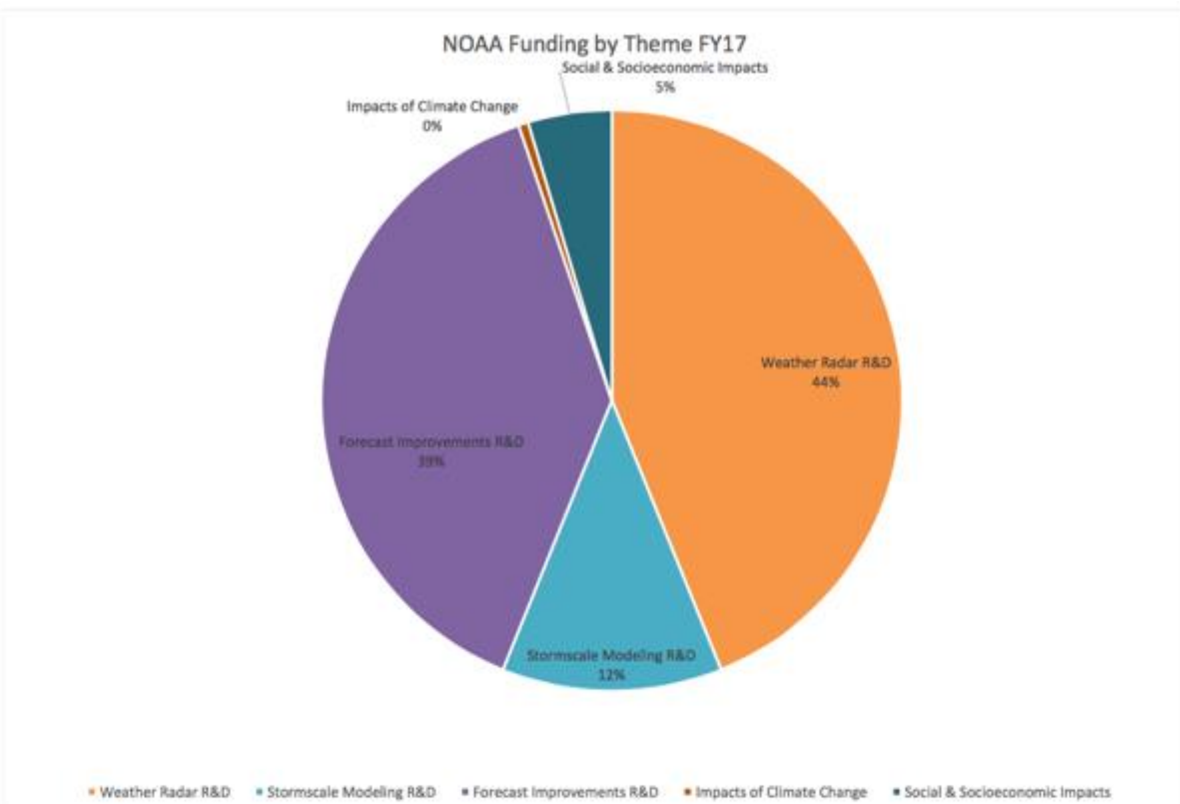
- NOAA Partners Communications, Public Affairs, and Outreach
- CIMMS Staff Outreach at WDTD

Awards and Honors

See Appendix A.

Distribution of NOAA Funding by CIMMS Task and Research Theme





CIMMS Executive Board and Council of Fellows Meeting Dates and Membership

Executive Board meetings were held on September 12, 2016 and April 27, 2017. Membership was as follows:

- Dr. Randy Peppler (Chair), Interim Director, CIMMS, and Lecturer, Department of Geography and Environmental Sustainability, OU
- Dr. Robert Palmer, Associate Vice President for Research, Executive Director, ARRC, and Professor and Tommy C. Craighead Chair, School of Meteorology, OU (Provost designated)
- Dr. Carol Silva, Director, CRCM, and Associate Professor of Political Science, OU (Provost designated)
- Dr. Kirsten de Beurs, Chair and Associate Professor, Department of Geography and Environmental Sustainability, OU (Provost designated)
- Mr. Lans Rothfusz, Deputy Director, NSSL (OAR designated)
- Dr. Jack Kain, Chief, Forecast Research and Development Division, NSSL (OAR designated)
- Mr. Richard Murnan, Radar Operations Center Applications Branch (NWS designated)
- Dr. Steven Weiss, Chief, Science Support Branch, SPC (NWS designated)
- Dr. Boon Leng Cheong, Research Scientist, ARRC (Elected from Assembly of Fellows)
- Dr. David Turner, Research Meteorologist, NSSL (Elected from Assembly of Fellows)
- Dr. Ming Xue, Director, CAPS (Elected from Assembly of Fellows in spring 2017 to replace David Turner)
- Mr. David Andra, Meteorologist-in-Charge, Norman NWS WFO (*ex-officio* member)
- Dr. Steven Koch, Director, NSSL (*ex-officio* member)
- Mr. Ed Mahoney, Director, WDTD (*ex-officio* member)
- Dr. Russell Schneider, Director, SPC (*ex-officio* member)
- Mr. Terry Clark, Director, ROC (*ex-officio* member)
- Mr. John Ogren, Director, NWSTC, and Chief Learning Officer, NWS (*ex-officio* member)
- Dr. David Parsons, Chair, OU School of Meteorology, Associate Director, CAPS, and Mark and Kandi McCasland Professor of Meteorology (*ex-officio* member)
- Dr. Berrien Moore, Dean, OU College of Atmospheric and Geographic Sciences, OU Vice President, Weather & Climate Programs, School of Meteorology Chesapeake Energy Corporation Chair in Climate Studies, and Director, National Weather Center (*ex-officio* member)

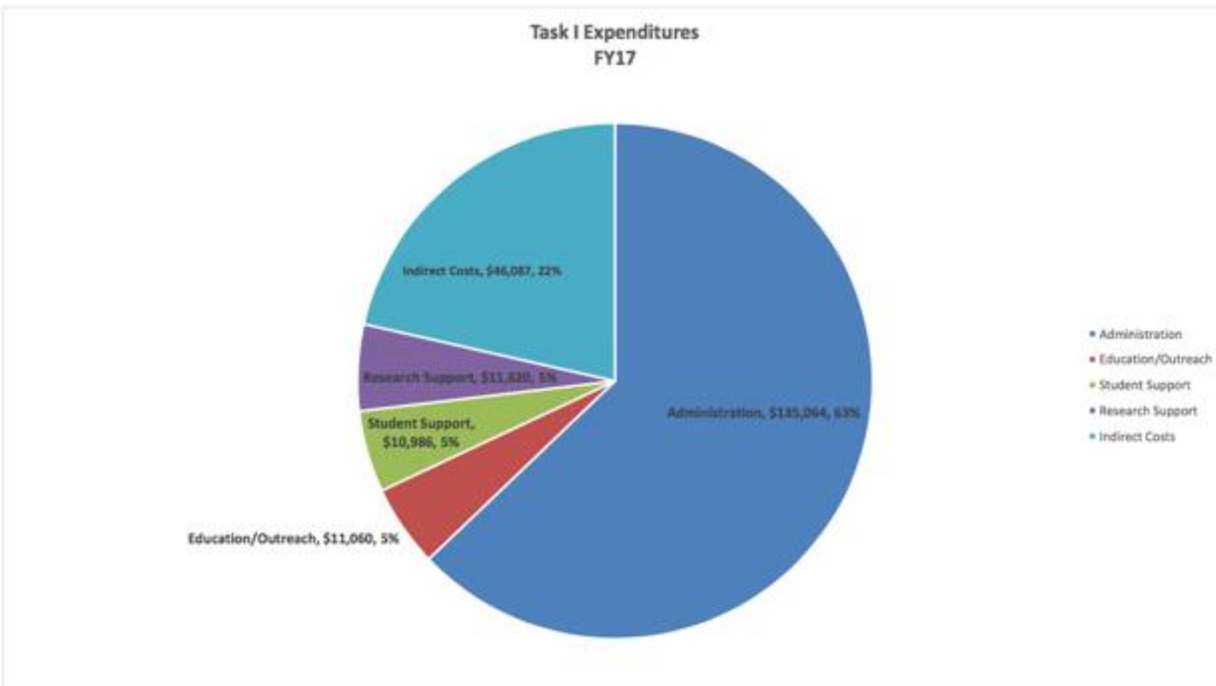
No Council of Fellows meetings took place during the fiscal year. Membership was as follows:

- Dr. Jeffrey B. Basara, Associate Professor of Meteorology, OU
- Dr. Michael I. Biggerstaff, Professor of Meteorology, OU
- Dr. Howard B. Bluestein, George Lynn Cross Research Professor of Meteorology, OU
- Dr. Keith Brewster, Senior Scientist and Associate Director, CAPS, OU
- Dr. Harold E. Brooks, Research Meteorologist and Team Leader, Mesoscale Applications Group, NSSL, and Adjunct Professor of Meteorology, OU
- Dr. Frederick H. Carr, Professor of Meteorology OU
- Dr. Steven Cavallo, Assistant Professor of Meteorology, OU
- Dr. Boon Leng Cheong, Research Scientist, ARRC, OU
- Dr. Phillip Chilson, Professor of Meteorology, OU
- Dr. Adam J. Clark, Research Meteorologist, NSSL
- Mr. Terrence Clark, Director, ROC
- Dr. Michael Coniglio, Research Scientist, NSSL
- Dr. Kirsten de Beurs, Chair and Associate Professor of Geography and Environmental Sustainability, OU
- Dr. Michael W. Douglas, Retired Research Scientist, NSSL
- Dr. Richard J. Doviak, Senior Engineer, Doppler Radar and Remote Sensing Research Group, NSSL, and Affiliate Professor of Meteorology and of Electrical and Computer Engineering, OU
- Dr. Kelvin K. Droegemeier, Vice President for Research and Regents' Professor, OU
- Dr. Claude E. Duchon, Emeritus Professor of Meteorology, OU
- Dr. Chris Fiebrich, Associate Director, OCS

- Dr. Jack Friedman, Research Scientist, CASR, OU
- Dr. Caleb Fulton, Assistant Professor of Electrical and Computer Engineering, OU
- Dr. Jidong Gao, Research Scientist, NSSL
- Dr. Nathan Goodman, Associate Professor of Electrical and Computer Engineering, and Director of Research, ARRC, OU
- Dr. J.J. Gourley, Research Scientist, NSSL
- Dr. Pamela Heinselman, Research Scientist, NSSL
- Mr. Kurt Hondl, Research Meteorologist, NSSL
- Dr. Yang Hong, Associate Professor of Civil Engineering and Environmental Sciences, OU
- Mr. Ken Howard, Research Meteorologist, NSSL
- Mr. Michael Jain, Acting Chief, Radar Research & Development Division, NSSL
- Dr. Hank Jenkins-Smith, Associate Director, CASR, and Professor of Political Science, OU
- Dr. Israel Jirak, Science and Operations Officer, SPC
- Dr. David P. Jorgensen, Chief, Warning Research & Development Division, NSSL
- Dr. Jack Kain, Chief, Forecasting Research & Development Division, NSSL
- Dr. Petra Klein, E. K. Gaylord Presidential Professor and Associate Professor of Meteorology, OU
- Dr. James F. Kimpel, Director, Emeritus NSSL, and Emeritus Professor of Meteorology, OU
- Dr. Kevin Kloesel, Director, OCS, and Associate Professor of Meteorology, OU
- Dr. Steven Koch, Director, NSSL
- Dr. Fanyou Kong, Research Scientist, CAPS, OU
- Dr. Daphne LaDue, Research Scientist, CAPS, OU
- Dr. S. Lakshmivarahan, George Lynn Cross Research Professor of Computer Science, OU
- Dr. Lance M. Leslie, Robert E. Lowry Chair and George Lynn Cross Professor of Meteorology, OU
- Dr. Donald R. MacGorman, Research Physicist, Convective Weather Research Group, NSSL, and Affiliate Professor of Meteorology and of Physics and Astronomy, OU
- Mr. Ed Mahoney, Chief, WDTD
- Dr. Edward Mansell, Research Scientist, NSSL
- Dr. Patrick Marsh, Techniques Development Meteorologist, SPC
- Dr. Elinor Martin, Assistant Professor of Meteorology, OU
- Dr. Amy McGovern, Associate Professor of Computer Science, OU
- Dr. Renee McPherson, Director of Research, South Central Climate Science Center, and Associate Professor of Geography and Environmental Sustainability, OU
- Dr. Berrien Moore III, Vice President for Weather and Climate Programs, Dean, College of Atmospheric and Geographic Sciences, Director, National Weather Center, and Chesapeake Professor of Meteorology, OU
- Dr. Mark L. Morrissey, Professor of Meteorology, OU
- Mr. Richard Murnan, Radar Meteorologist, ROC
- Mr. John Ogren, Chief Learning Officer, NWS
- Dr. Robert D. Palmer, Associate Vice President for Research, Executive Director, ARRC, and Tommy Craighead Chair and Professor of Meteorology, and OU
- Dr. David Parsons, Director, School of Meteorology, Mark and Kandi McCasland Professor of Meteorology, OU
- Dr. Robert Rabin, Research Scientist, NSSL
- Dr. Michael B. Richman, E. K. Gaylord Presidential Professor of Meteorology, OU
- Mr. Lans Rothfusz, Deputy Director, NSSL
- Dr. Jessica Ruyle, Assistant Professor of Electrical and Computer Engineering, OU
- Dr. Jorge Salazar-Cerreno, Assistant Professor of Electrical and Computer Engineering, OU
- Dr. Russell Schneider, Director, SPC
- Dr. Mark Shafer, Director of Climate Services, OCS, and Assistant Professor of Geography and Environmental Sustainability, OU
- Dr. Alan M. Shapiro, American Airlines Professor and President's Associates Presidential Professor of Meteorology, OU
- Dr. Hjalti Sigmarsson, Assistant Professor of Electrical and Computer Engineering, OU
- Dr. Carol Silva, Director, CRCM, and Professor of Political Science, OU
- Dr. Paul Spicer, Professor of Anthropology, OU
- Dr. Jerry M. Straka, Professor of Meteorology, OU
- Dr. Aondover A. Tarhule, Associate Dean, College of Atmospheric and Geographic Sciences, and Associate Professor, Department of Geography and Environmental Sustainability, OU
- Dr. David Turner, Research Scientist, Global Systems Division, ESRL
- Dr. Xuguang Wang, Associate Professor of Meteorology, and Presidential Research Professor, OU

- Mr. Steven J. Weiss, Chief, Science Support Branch, SPC
- Dr. Louis J. Wicker, Research Meteorologist, Convective Weather Research Group, NSSL, and Affiliate Associate Professor of Meteorology, OU
- Dr. Qin Xu, Research Meteorologist, Models and Assimilation Team, NSSL, and Affiliate Professor of Meteorology, OU
- Dr. Ming Xue, Director, CAPS, and Professor of Meteorology, OU
- Dr. Mark Yeary, Professor of Electrical and Computer Engineering, OU
- Dr. Tian-You Yu, Director of Operations, ARRC, and Professor of Electrical and Computer Engineering, OU
- Dr. Guifu Zhang, Professor of Meteorology, OU
- Dr. Jian Zhang, Research Hydrometeorologist, NSSL
- Dr. Yan Zhang, Associate Professor of Electrical and Computer Engineering, OU
- 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, and Affiliate Professor of Meteorology and of Electrical and Computer Engineering, OU

General Description of Task I Expenditures



RESEARCH PERFORMANCE

Theme 1 – Weather Radar Research and Development

NSSL Project 2 – Hydrometeorology Research

NOAA Technical Leads: Kenneth Howard and Jian Zhang (NSSL)

NOAA Strategic Goal 2 – *Weather-Ready Nation – Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Task II

Objectives
The hydrometeorology research objectives primarily center around dual-polarized radar research and quantitative precipitation estimations (QPEs). The following are specific objectives to the hydrometeorological research group:

- Operational implementation of MRMS v11.0
- Virtual MRMS system to test experimental updates prior to operational implementation
- Assimilation of radar data across the Caribbean
- Quality control of radar data for MRMS
- Updated radar blockage information for WSR-88D radars in MRMS
- Updated physically-based 2D seamless reflectivity mosaicking for MRMS QPE generation and RQI
- Advancements in the ingest and quality control of precipitation gauges in MRMS
- Development of a merged QPE using radar and rain gauge precipitation data
- Integrating an evaporation correction scheme to real-time precipitation rates in MRMS
- MRMS QPE evaluations versus single source radar QPE products
- Development and verification of a dual-pol synthetic radar QPE
- The MRMS Experimental Testbed for Operational Products (METOP)
- The meteorological Phenomena Identification near the Ground (mPING) project
- mPING random forest modeling
- Radar extrapolation for very short-term quantitative precipitation forecasts
- Cloud detection algorithm for MRMS
- Mobile radar deployment for snow and gap-filling radar analysis in Alamosa, CO
- Enhanced accuracy of radar snowfall estimations using new Z-S relationships
- Continued development of web-based tools and displays for product analysis

Accomplishments

1. Operational Implementation of the Multi-Radar Multi-Sensor System v11.0

Carrie Langston, Karen Cooper, Brian Kaney, Darrel Kingfield, Lin Tang, Youcun Qi, Ami Arthur, Zac Flamig, Jeff Brogden, and Steven Martinaitis (CIMMS at NSSL), and Heather Grams (ROC)

On December 1, 2016, the Multi-Radar Multi-Sensor (MRMS) system was upgraded from v10.5 to v11.0 at the National Centers for Environmental Prediction (NCEP) Central Operations (NCO) as part of the Integrated Dissemination Program (IDP). This was a major update that included new algorithm suites and significant upgrades to existing algorithm suites.

The initial code drop for MRMS v11.0 was provided to NCO at the end of fiscal year 2016, and a lengthy summary of the updates was reported in FY16 CIMMS annual report. CIMMS staff provided source code, documentation and support to NCO for troubleshooting the operational system and for subsequent updates. Below is an abbreviated summary for reference:

<u>Infrastructure/System Changes</u>:

- Reduced overall system I/O by centralizing the data storage.
- Centralized/improved the MRMS system update process.

<u>Severe Weather Product Updates</u>:

- Lightning:
  - Switched to an operational lightning feed, which increased stability.
  - Improved readability of lightning products based on users' feedback.
- AzShear and Rotation Tracks:
  - Improved algorithm performance near the radar and handling of super-resolution data, which created a more skillful rotation track.
- New Products:
  - NIDS formatted products (for SPC): Vertical Integrated Ice
  - Resampled composite reflectivity and reflectivity at the lowest altitude to a 5 × 5 km resolution. These 5-km products are on the SBN with WMO codes YAUC09 and YAUS01, respectively.

<u>Hydrometeorological Product Updates</u>:

- Model Usage:
  - Incorporated the 3-km HRRR into the Model Remap field.
- Radar Quality Control:
  - Canadian Radar Network: Major improvements to mitigate ground clutter contamination, especially during anomalous propagation.
  - WSR-88D Radar Network: Refinements made to accept new scan modes, improve melting layer detection, and wind farm detection.
- Gauge Ingest and Quality Control:

  - Reduced data latency and added logic to account for areas with no radar coverage along with improved gauge data quality control associated winter precipitation.
- Quantitative Precipitation Estimates (QPEs)
  - Radar-Only QPE: Better handles data voids near the radar sites and wind farms due to the clutter suppression, and reduced warm season wet bias in the northern and central plains by implementing a tropical rain rate climatology scheme.
  - Locally Gauge-Corrected Radar QPE: Increased the robustness by accounting for potential sampling discrepancies between radar and gauge. Computational and I/O efficiency were increased.
  - Mountain Mapper QPE: The radar-based precipitation mask was removed, which allows for more gauge influence in areas with poor radar coverage.

RIDGE-II Updates:
- Increased geoTIFF resolution for single radar products.
- Increased range of geoTIFF for single radar products.

New Algorithms:
- AutoNowCaster (ANC): ANC is an algorithm managed by MDL. It generates a Convective Likelihood and a Final Forecast (60-min forecast of reflectivity) product.
- Flooded Location and Simulated Hydrographs (FLASH): FLASH is an algorithm developed by NSSL and CIMMS. It generates several products, such as Unit Streamflow, Streamflow, and Soil Saturation products from a hydrologic model and QPE comparison tools like Average Recurrence Intervals, and QPE-to-FFG Ratio products.

The implementation of v11.0 required new virtual machines (VMs). Working with NCO, two VMs were created, configured, and tested. One VM generates the AutoNowCaster products. The other is used to run FLASH.

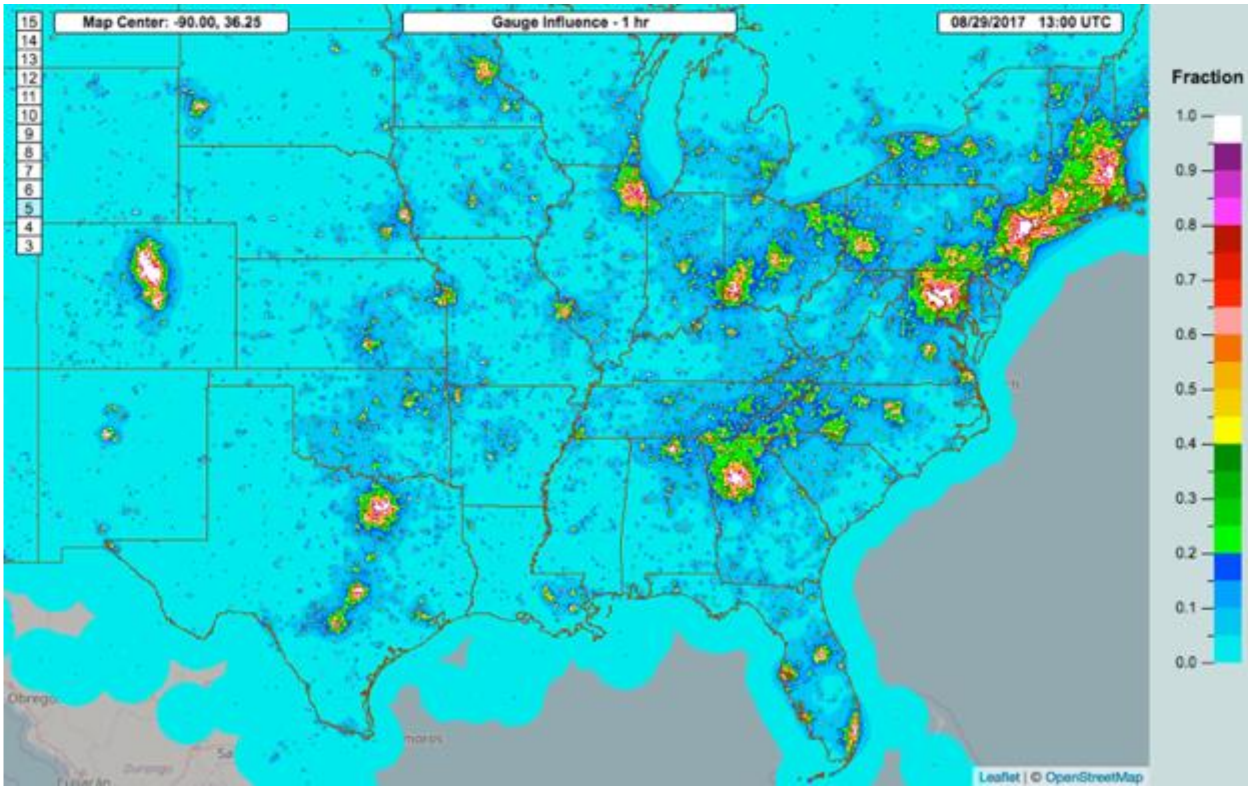
To assist NCO with testing and implementing MRMS v11.0, all standard MRMS documents were updated.

- *Software Design* -- Detailed definition of the MRMS data flow and processing modules
- *Build Instructions* -- Steps for compiling the various software components of MRMS
- *Implementation Instructions* -- Steps for installing and configuring MRMS on a server or virtual machine
- *Execution Instructions* -- Steps for starting, stopping and generally managing MRMS processes on a server or virtual machine.
- *Testing and Troubleshooting* -- Instructions for testing all the individual components of MRMS along with suggestions for troubleshooting common problems.

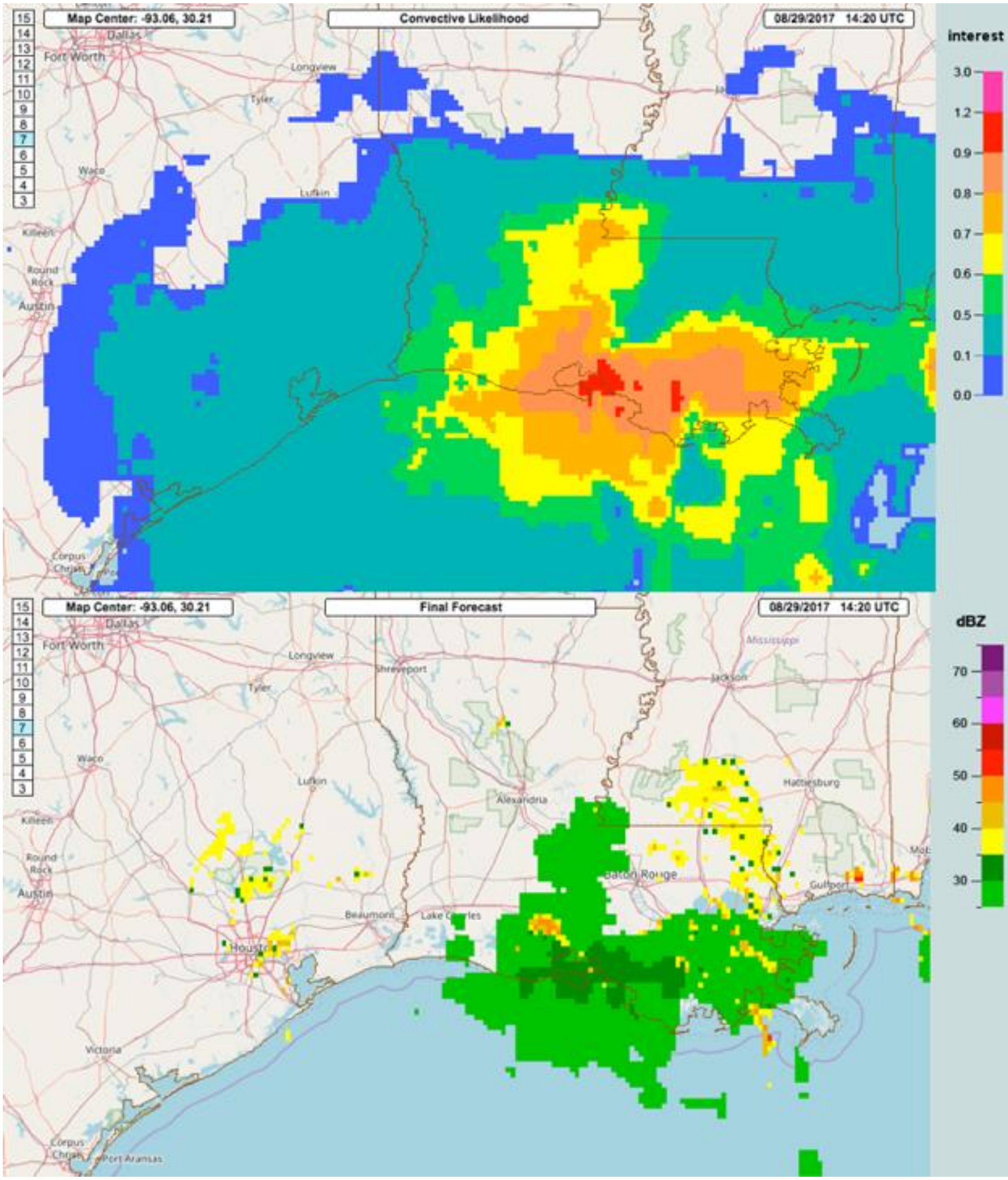
- *NCO server spreadsheet* -- A spreadsheet with three worksheets detailing on a virtual machine (VM) by VM basis the assigned processing, computing resources, lists of input and output data, and system configuration files.

In addition, two MRMS v11.0 specific documents were provided to 1) assist NCO staff in understanding important components of the update and 2) install FLASH. MDL provided all the documentation for ANC via VLab. Not including ANC, the MRMS on-boarding documentation consists of approximately 210 pages and 3 companion worksheets. A copy of the documentation can be made available if requested.

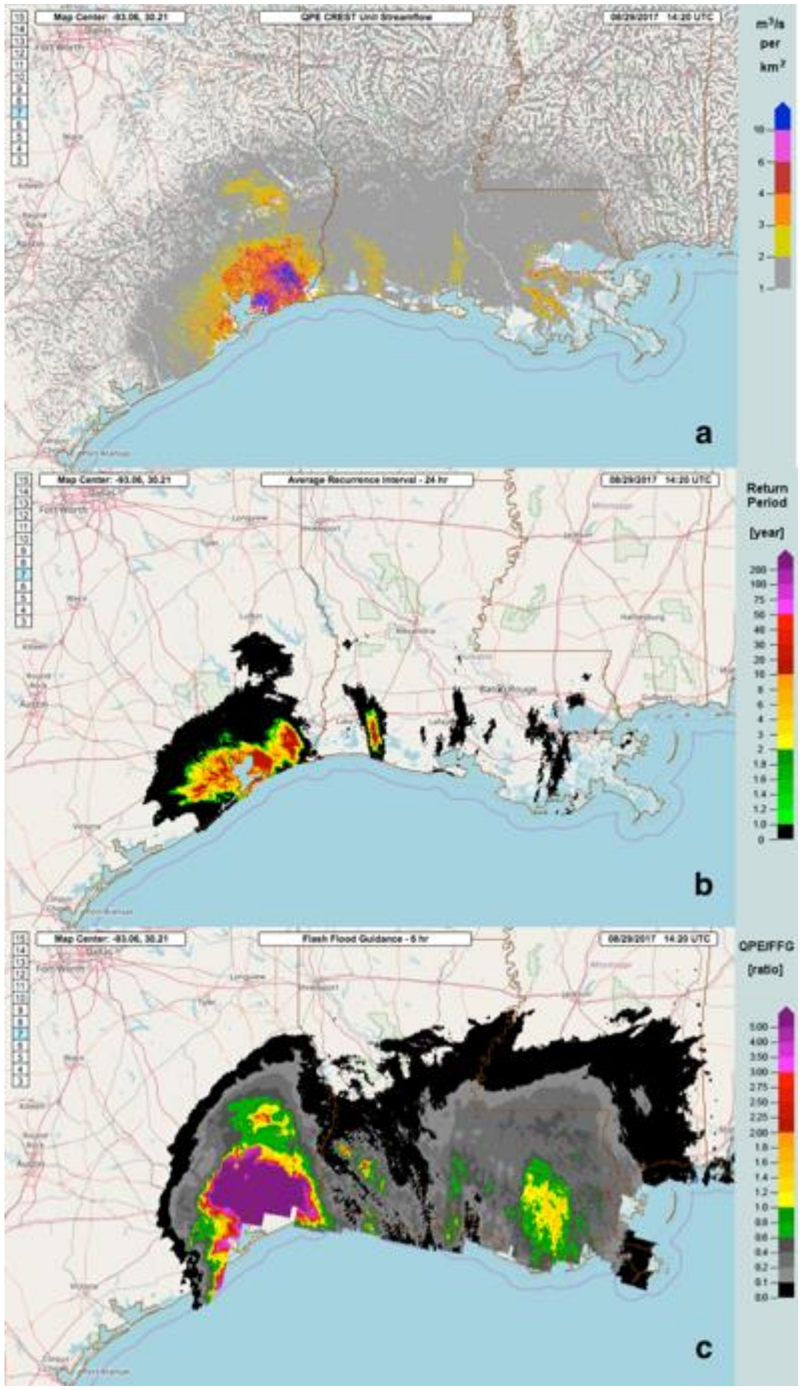
The MRMS v11.0 work is complete.



Sample image of the 1-hour Gauge Influence Index, which is a new product for MRMS with the implementation of v11.



Sample images of AutoNowCaster's (top) Convective Likelihood and (bottom) Final Forecast, which are new with MRMS v11.0. Note: Final Forecast is the 1-hour reflectivity forecast.



Sample images of the FLASH (a) CREST Unit Streamflow, (b) 24-hour Average Recurrence Interval, and (c) 6-hour QPE to Flash Flood Guidance ratio products.

Publications

Smith, T. M., V. Lakshmanan, G. J. Stumpf, K. L. Ortega, K. Hondl, K. Cooper, K. M. Calhoun, D. M. Kingfield, K. L. Manross, R. Toomey, J. Brogden, 2016: Multi-Radar Multi-Sensor (MRMS) severe weather and aviation products: Initial operating capabilities. *Bulletin of the American Meteorological Society*, **97**, 1617-1630.

2. NSSL Virtual Multi-Radar Multi-Sensor (VMRMS) System

Karen Cooper, Carrie Langston, Lin Tang, and Alicia Keys (CIMMS at NSSL), and the NSSL Information Technology Services Group (AceInfo Solutions)

A key NSSL strategy to maintain the stability of MRMS for research and operational environments is to host development efforts on a computing infrastructure similar to what is used at NCO. To fill this need, a development and testing system (called VMRMS) is maintained at NSSL. Using VMRMS and development resources at NCO, MRMS v11.0 was delivered to NCO and implemented operationally in December 2016. The algorithms and configurations for the next operational MRMS are tested and verified on VMRMS before they're given to NCO. VMRMS also houses experimental products in their earliest stages of development.

Experimental products implemented in FY17 include the following:

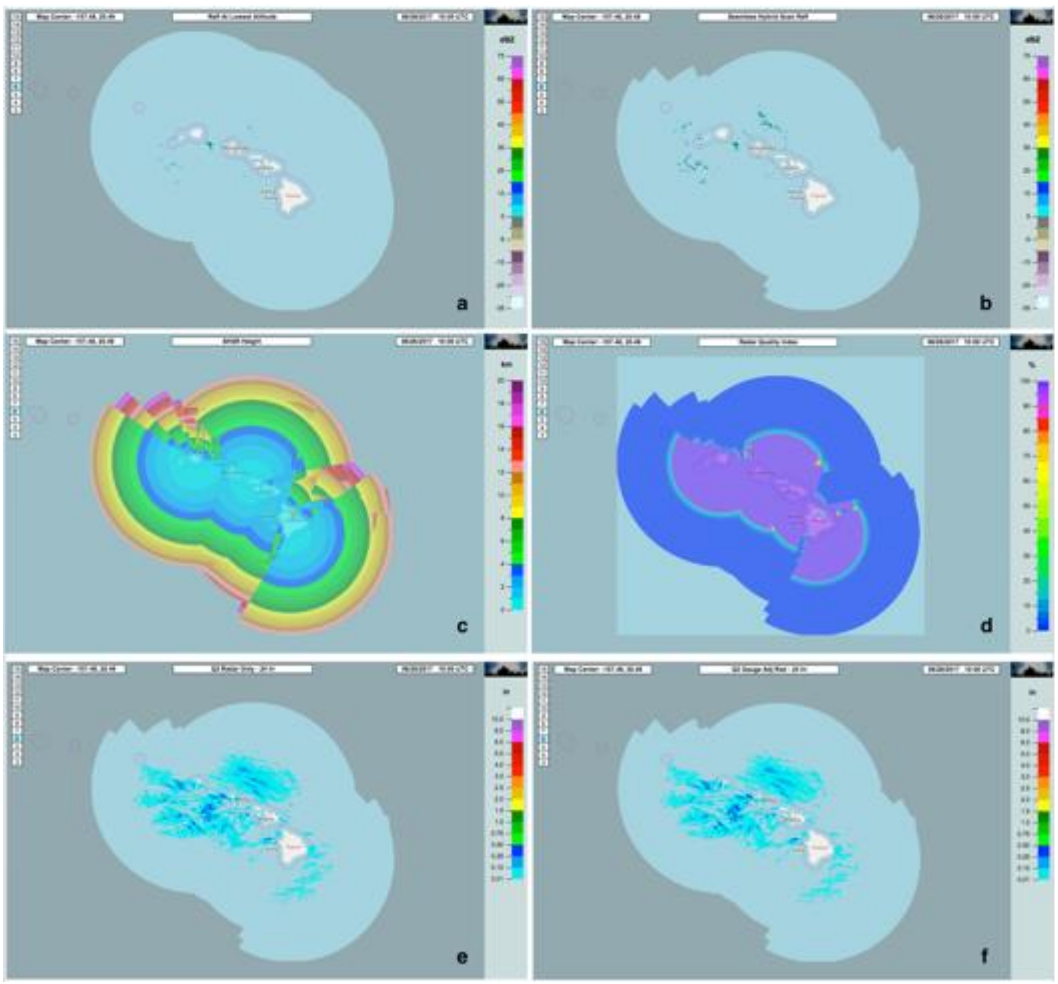
- 3D mosaics of spectrum width, RhoHV, K_{DP}, and Z_{DR}.
- Incorporation of MADIS gauges in all gauge-based QPEs, which increased MRMS's gauge observations from approximately 7,000 to 19,000.
- Incorporation of 1-hour HydroEstimator and SCaMPR satellite QPEs for Gauge QC purposes.
- Dual pol QPE – Deriving precipitation rates using dual pol moments
- Synthetic QPE – Blending of traditional single pol and dual pol precipitation rates and generating 1-72 hour QPEs
- Multi-Sensor Merged QPE – Blending hourly Locally Gauge-Corrected Radar QPE and Mountain Mapper QPE and generating 1-72 hour merged QPEs.
- Echo Top – Improved interpolation and extrapolation between reflectivity levels.
- Severe Weather Algorithms – Background values are more consistent.
- Azimuthal Shear – Spike removal option added.
- Incorporation of non-US radars in the Caribbean domain (e.g., Grand Cayman Island) and exploration of additional radars (e.g., Sabancuy, Mexico and Belize)
- Expansion of the MRMS product suite for Hawaii – Hawaii was initially configured for a very limited number of products (raw/QC'd BREF, raw/QC'd CREF, Echo Top 18dBZ, Level III base HCA). On VMRMS, the product suite for Hawaii was expanded to include significantly more products. Approximately 90% of the products available for the MRMS CONUS domain are now available for Hawaii. Remaining work includes finalizing FLASH and incorporating more environmental data to aid in QPE derivations.

VMRMS computing resources increased in FY17. The following list outlines this growth:

- Dell Chassis: Increased from 3 to 4
- Dell Blade Servers: Remains at 24
- Processor Count: Remains at 246 to
- CPU Capacity: Remains at 1.92 THz
- Memory: Remains at 9.25 TB

- Storage (NetApp, Network Attached Storage): Remains at 40 TB for real-time data processing. 300 TB was added to support METOP and provide archive space for VMRMS. Connectivity is 10 GB.
- Virtual Machine Count: Increased from 75 to 81

In addition, a new effort to better document the VMRMS system and MRMS in general is underway. In February 2017, a new Wiki was configured on an internal NSSL server. When possible, members of SHMET (along with SWAT) are populating the Wiki with a range of basic and detailed information. For example, there are pages defining Volume Coverage Patterns, tracking the status of non-US radars for the Caribbean domain, and a change log for all updates made to VMRMS. This Wiki is available on NSSL's network only but excerpts can be made available if requested. This project is ongoing.



Sample images of products from the expanded Hawaii domain, which include (a) Reflectivity at Lowest Altitude, (b) Seamless Hybrid Scan Reflectivity, (c) SHSR Height, (d) Radar Quality Index, (e) 24-hour Radar-Only QPE, and (f) 24-hour Locally Gauge-Corrected Radar QPE.

3. Caribbean Radar Data Assimilation Project

José Meitín, Karen Cooper, and Heather Reeves (CIMMS at NSSL)

NSSL is tasked with compiling the technical information on individual radars that are participating in the Caribbean basin raw data assimilation project. The earlier phase of the project involved high priority radar sites as determined by the National Hurricane Center. The continued collection of data will help in developing the MRMS Caribbean domain. The following bullets describe the status of acquiring data from the various meteorological services across the Caribbean. This project is ongoing.

- <u>Cayman Islands National Weather Service</u>: We continue to receive raw base-level radar data from this site.
- <u>Cuba Instituto de Meteorología (INSMET)</u>: As part of the previous administration normalization efforts, NOAA and INSMET negotiated a Memorandum of Understanding which included data exchange opportunities. Initial discussions were held for a possible site visit by a U.S. delegation possibly to include CIMMS researchers. Official travel requests were submit through INSMET to the Cuban Foreign Ministry. At about that time, the federal government changed administrations and any momentum these discussions may have attained were suspended. Our attempts to transfer some sample data files were unsuccessful due to the poor quality Internet bandwidth that is available within INSMET in Cuba. Technical hardware to mitigate this problem is commercially available but out of reach to the data providers. Further discussions are on hold at the moment.
- <u>Jamaica Meteorological Service</u>: After staff changes at the Weather Office, renewed discussions with the current manager yielded an exchange of sample data files for this site. It was determined that the formats and structure available did not offer sufficient granularity to merit inclusion in the MRMS composite. In order to get the temporal and spatial resolution necessary would require a proprietary software license. This radar is expected to be replaced by the end of 2017, we will wait until the new radar is operational (without requiring proprietary licensing) to begin data exchange.
- <u>Bahamas Department of Meteorology:</u> Four new Vaisala Doppler radars were acquired for New Providence, Grand Bahama Island, Long Island and Great Abaco. As of May 2017, the new radar at New Providence (Nassau) was in test/acceptance mode. We have made a request for data exchange from this site once it becomes operational. Our request is pending.
- <u>Mexico Servicio Meteorológico Nacional (SMN)</u>: We have been receiving data from the Sabancuy (Campeche/Yucatan) radar for several months. Recently, it was reported that this site was experiencing hardware problems.
- <u>National Meteorological Service of Belize</u>: After management staff retirement, we have received approval for data from this radar site. The hardware specifications of this radar are similar to those at Cayman Islands therefore we will complete the set up for real time data exchange soon.

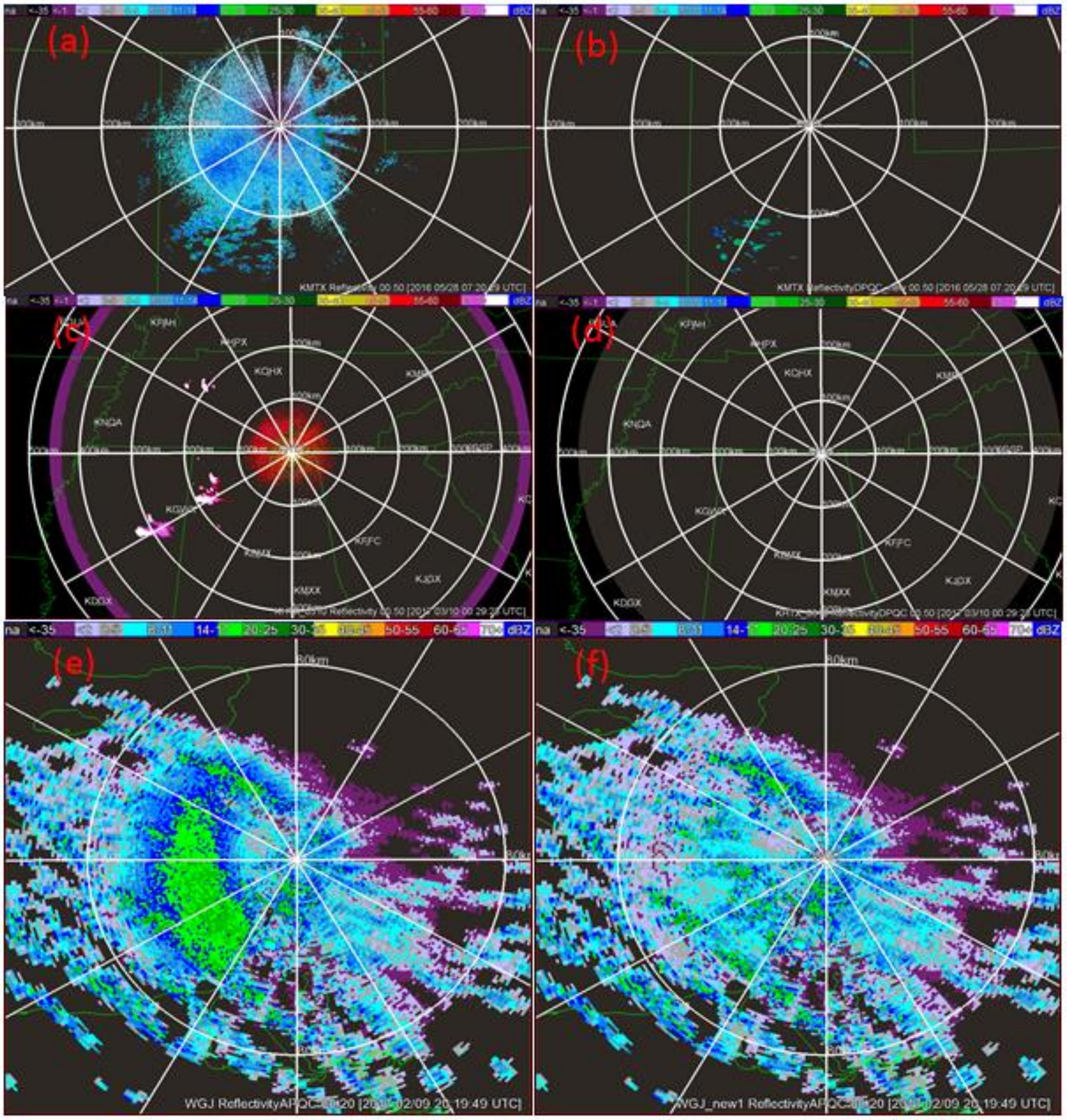
- Meteorological Department Curaçao: Another site with personnel changes. We made a formal request for real time data exchange from this Vaisala radar site, which is under consideration by their management board.

4. MRMS Radar Data Quality Control

Lin Tang and Carrie Langston (CIMMS at NSSL), and Jian Zhang and Kenneth Howard (NSSL)

The Multi-Radar Multi-Sensor (MRMS) system ingests 3D volume scan data from about 146 S-band dual-polarization Weather Surveillance Radar-1988 Doppler (WSR-88D) radars and about 30 C-band single-polarization weather radars operated by Environment Canada. Based on the real-time observation and users' feedbacks, the quality control (QC) process of input WSR-88D and Canadian radar data has been continuously refined.

The QC updates during this year include the improvements in retaining the light precipitation and handling the hardware failure for WSR-88D radars, as well as in mitigating the lake clutter near the Canadian radar at Montreal river (WGJ). It is challenging to separate the light precipitation echoes from clutter when the signal to noise ratio is low. The figure below shows the updated output is able to lower false alarms and retain more light precipitation echoes. Testing pattern during the radar maintenance were observed rarely, a couple of scans per year, yet the downstream QPE products and hydrology model could be severely contaminated from the pattern clutter. A scheme was added to completely clear up the possible contaminated returns due to the radar hardware. Lake clutter mitigation was also performed in these quality control steps. When the lake clutter is mixed with precipitation echoes, the contaminated measurement is corrected using the echoes from higher elevation scans. These QC updates will be implemented in the operational MRMS system after real time testing. This project is ongoing.



Raw reflectivity (left column) and quality controlled reflectivity (right column) fields for (a-b) clutter removal while retaining light precipitation from KMTX at 0720 UTC 28 May 2016, (c-d) testing patterns from KHTX at 0029 UTC 10 March 2017, and (e-f) lake clutter mitigation from WGJ at 2019 UTC 9 February 2017.

5. Updated Blockage Data for WSR-88D Radars Used in the MRMS System

Lin Tang, Ami Arthur, and Carrie Langston (CIMMS at NSSL), and Jian Zhang (NSSL)

Accurate information about the blockage plays an important role in the proper interpretation of reflectivity data. In the Multi-Radar-Multi-Sensor (MRMS) system, the occultation data affects both severe weather and quantitative precipitation estimation products.

After the MRMS system was transitioned into operations in 2014, forecasters reported occasional removal of weather echoes and inaccurate power correction due to inaccurate beam blockage information. The potential sources of the error include 1) the terrain data resource used in the MRMS, 2) the raw resolution of blockage field, 3) conservative blockage parameter settings to avoid ground clutter in the single-pol radar era, and 4) outdated information of non-standard blockage from manmade buildings or trees. In the work of updating the blockage data, the Shuttle Radar Topography Mission (SRTM) digital elevation data was used to replace the national elevation dataset (NED). The blockage calculation method and parameter settings were refined for the dual-pol radar era. The updated blockage has been implemented in the real-time system for an improved MRMS performance in storm detection, forecasting, as well as the precipitation products. This work was funded in part through the CIMMS Director's Discretionary Research Fund. This project is complete.

Modifications	MRMS Blockage (Before)	MRMS Blockage (After)
Terrain Resource	National Elevation Dataset (NED)	Shuttle Radar Topography Mission (SRTM)
Terrain Aggregation	Maximization	No Aggregation
Terrain Resolution	9 arc secs (~250 m)	1 arc sec (~30m)
Minimum Blockage Clearance	50 meters	No Clearance
Power Distribution Function (Horizontal)	Simplified Bessel Function	Gaussian
Power Distribution Function (Vertical)	Uniform Distribution	Gaussian

6. A Physically Based Two-Dimensional Seamless Reflectivity Mosaic for Radar QPE in the MRMS System

Youcun Qi (CIMMS at NSSL) and Jian Zhang (NSSL)

The U.S. Weather Surveillance Radar-1988 Doppler (WSR-88D) network has provided meteorologists and hydrologists with quantitative precipitation observations at an unprecedented high spatial–temporal resolution since its deployment in the mid-1990s. Since each radar can only cover a maximum range of 460 km, a mosaic of multiple-radar observations is needed to generate any national-scale products. The Multi- Radar Multi-Sensor (MRMS) system utilizes a physically based two-dimensional mosaicking algorithm of the WSR-88D data to generate seamless national quantitative precipitation estimation (QPE) products. For areas covered by multiple radars, the mosaicking scheme first determines if precipitation is present by checking the lowest-altitude observation. If the lowest observed radar data indicate no precipitation, then the mosaicked value is set to no precipitation. Otherwise, a weighted mean of multiple-radar observations is taken as the mosaicked value. The weighting function is based on multiple factors, including the distance from the radar and the height of the observation with respect to the melting layer. The mosaic algorithm uses the physically lowest radar

observations with no/little blockage while maintaining a spatial continuity in the mosaicked field. The performance of the MRMS seamless radar mosaic algorithm was examined for various precipitation events of different characteristics. The updated scheme contains logic updates to mitigate discontinuities in the radar mosaicking process and refining the Radar Quality Index (RQI) logic, including updates on handling the freezing level data. This project is complete.

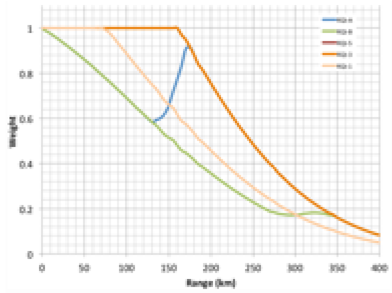
$$RQI_{hgt} = \begin{cases} 1 \; (h < frzl_0) \\ \min\left\{1, \exp\left[-\dfrac{h - frzl_{adj}}{H_0}\right]\right\} \; (h \geq frzl_0) \end{cases}$$

$$frzl_{adj} = \min\{frzl, frzl_0\}$$

Here, h is beam center height (in m or km above radar level), frzl is the freezing level height (in m or km above radar level). H_0 and $frzl_0$ are configurable parameters in m or km.

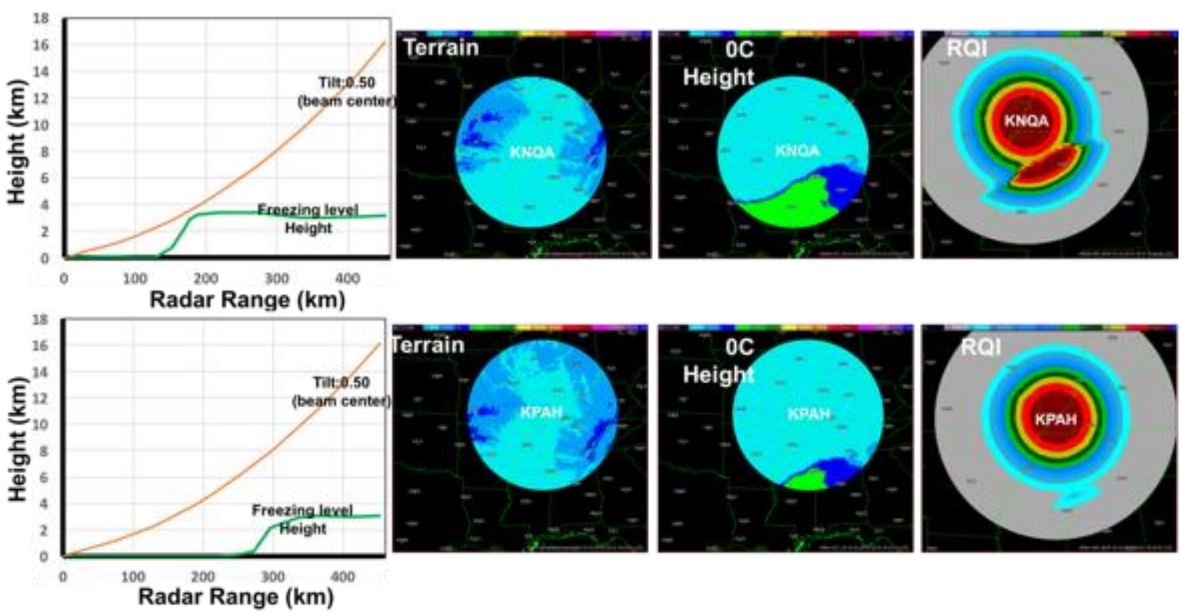
The figures here show examples with H_0 = 1.5km and $frzl_0$ = 3km. They can be adjusted to better reflect the relative quality of the radar QPE as a function of beam height and freezing level height.

This design would assure a continuous RQI across strong gradient of freezing level (see lower right panel for case A).



This figure shows five scenarios of different freezing level heights w.r.t. beam center height:
FRZ-A: case A on slide #1
FRZ-B: case B on slide #2
FRZ-5 (3,1): constant freezing level height of 5 (3,1) km above radar level.
The new RQI had discontinuities at the strong gradient of freezing level height.
A change may be made to the new RQI to avoid the discontinuity (see next slide).

Refined RQI logic with handling freezing level heights.



Example input fields and final RQI products for individual radar sites.

Publications

Qi, Y. and J. Zhang, 2017: A physically based two-dimensional seamless reflectivity mosaic for radar QPE in the MRMS system. *Journal of Hydrometeorology*, **18**, 1327-1340.

7. Advancements in Quality Control and Ingest of Gauge Observations in the MRMS System

Steven Martinaitis, Carrie Langston, Stephen Cocks, and Youcun Qi (CIMMS at NSSL), and Jian Zhang and Kenneth Howard (NSSL)

Surface rain gauge observations are regarded as "ground truth" when used to verify and calibrate radar-derived quantitative precipitation estimates (QPE). However, gauges not properly vetted by a quality control (QC) procedure can introduce erroneous statistical results and bias calibration. Continued advancements were made to the precipitation gauge ingest and QC algorithms to allow for a greater quantity of gauges to undergo QC and to modify decision-tree logic in the executable coding.

The gauge ingest script for the Multi-Radar Multi-Sensor (MRMS) system was modified to include networks obtained by the Meteorological Assimilation Data Ingest System (MADIS) along with the Hydrometeorological Automated Data System (HADS) as well as the Maricopa County, AZ ALERT network. Gauge observations from MADIS were in non-traditional formats (running accumulations, various 24-h accumulations, etc.), so additional logic was included to extract the hourly values. The increased the number of hourly, non-missing automated gauge observations from approximated 7,000 per hour to over 16,000 per hour. The latest version of the QC algorithm for the MRMS system included new outlier bounds for both liquid and liquid-equivalent gauge values. Additional logic was also included to use a satellite mask to remove gauges that experiencing post-event thaw or error that cannot be quality controlled due to lack of radar coverage.

Continuing long-term collaboration between the National Severe Storms Laboratory (NSSL) and other National Oceanic and Atmospheric Administration (NOAA) partners will address continued collection and QC of gauge observations and metadata, the identification of quality gauge observations within winter precipitation regimes by using collocated observations, and the feasibility of a real-time wind correction scheme. This project is ongoing.

8. Combining Ground and Radar-Based Precipitation Estimates with Rainfall Climatologies to Generate a Merged QPE

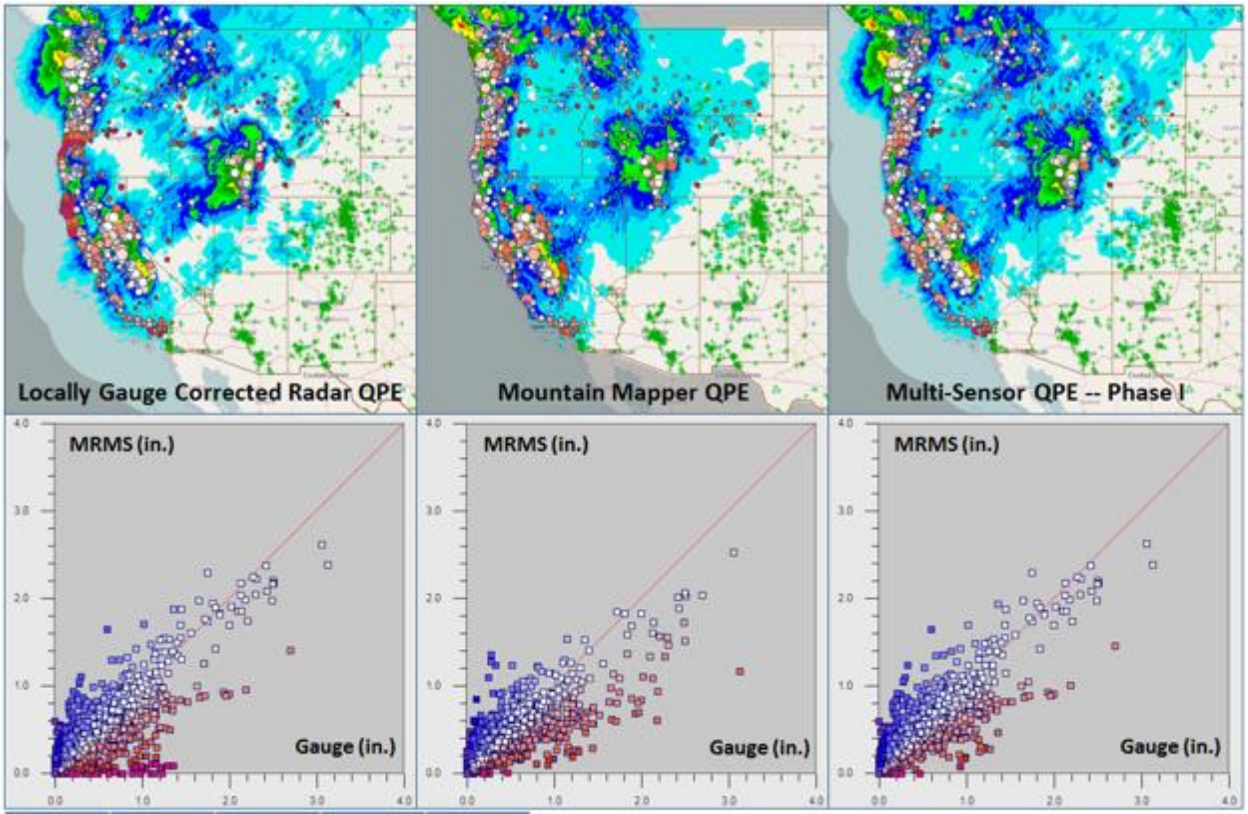
Steven Martinaitis, Carrie Langston, and Youcun Qi (CIMMS at NSSL), and Jian Zhang and Kenneth Howard (NSSL)

Different sources of QPE have varying strengths and challenges in generating deterministic surface precipitation values. These challenges are magnified in the western United States where there are significant gaps in radar coverage due to less dense coverage and beam blockage from complex terrain along with a sparse network of gauge observations. CIMMS scientists are developing a scheme to merge a radar-derived quantitative precipitation estimation (QPE) with gauge observations and a climatology-based QPE to provide a more accurate and comprehensive QPE coverage

across the conterminous United States in the Multi-Radar Multi-Sensor (MRMS) system. This is known as the MRMS Multi-Sensor QPE.

The first phase of the Multi-Sensor QPE would seamlessly blend locally-gauge corrected radar QPE (Q3GC) with the Mountain Mapper QPE (Q3MM), which is created by interpolating gauge observations onto the Parameter-elevation Relationships on Independent Slopes Model (PRISM) background rainfall climatology. The merging scheme utilizes the MRMS Radar Quality Index (RQI) as the primary weighting function to seamlessly blend the two QPE sources. Other factors that influenced the weight between Q3GC and Q3MM were the coverage of non-zero reflectivity values and the radius of influence of gauge observations. Results showed the Multi-Sensor QPE scheme improved upon statistical measures where radar QPE gaps from beam blockage and even lack of coverage from inoperative radars were successfully filled in using Mountain Mapper, especially during cool season atmospheric river or other more stratiform-based precipitation events. The ability of the scheme to use RQI allowed for increased retaining of radar data to capture the spatial variability of convective precipitation.

This first phase of the Multi-Sensor QPE is serving as an intermediate product for the more robust second phase, which will include GOES QPE and short-term quantitative precipitation forecasts from numerical models. The scheme will also be developed over the MRMS domains beyond the CONUS, with studies looking at potentially varying the weighs of the products to optimize QPE across each sector. This project is ongoing.



	Bias	ME	RMSE	CC
Q3GC	1.058	0.011	0.188	0.873
Q3MM	1.151	0.027	0.198	0.866
Q3MS	0.998	0.000	0.166	0.902

Comparison of MRMS Q3GC and Q3MM vs. Q3MS for 24-h Period Ending 1400 UTC 8 April 2017

Comparison of MRMS locally gauge-corrected radar QPE (Q3GC), Mountain Mapper QPE (Q3MM), and the Multi-Sensor QPE (Q3MS) – Phase I for 24–h period ending 1400 UTC 8 April 2017. Top row contains MRMS QPE with bubble plots comparing QPE against CoCoRaHS daily gauge observations. Second row contains scatter plots comparing QPE versus CoCoRaHS gauges with a statistic table in bottom left.

9. Integrating an Evaporation Correction Scheme to Real-Time Instantaneous Radar Rainfall Rates

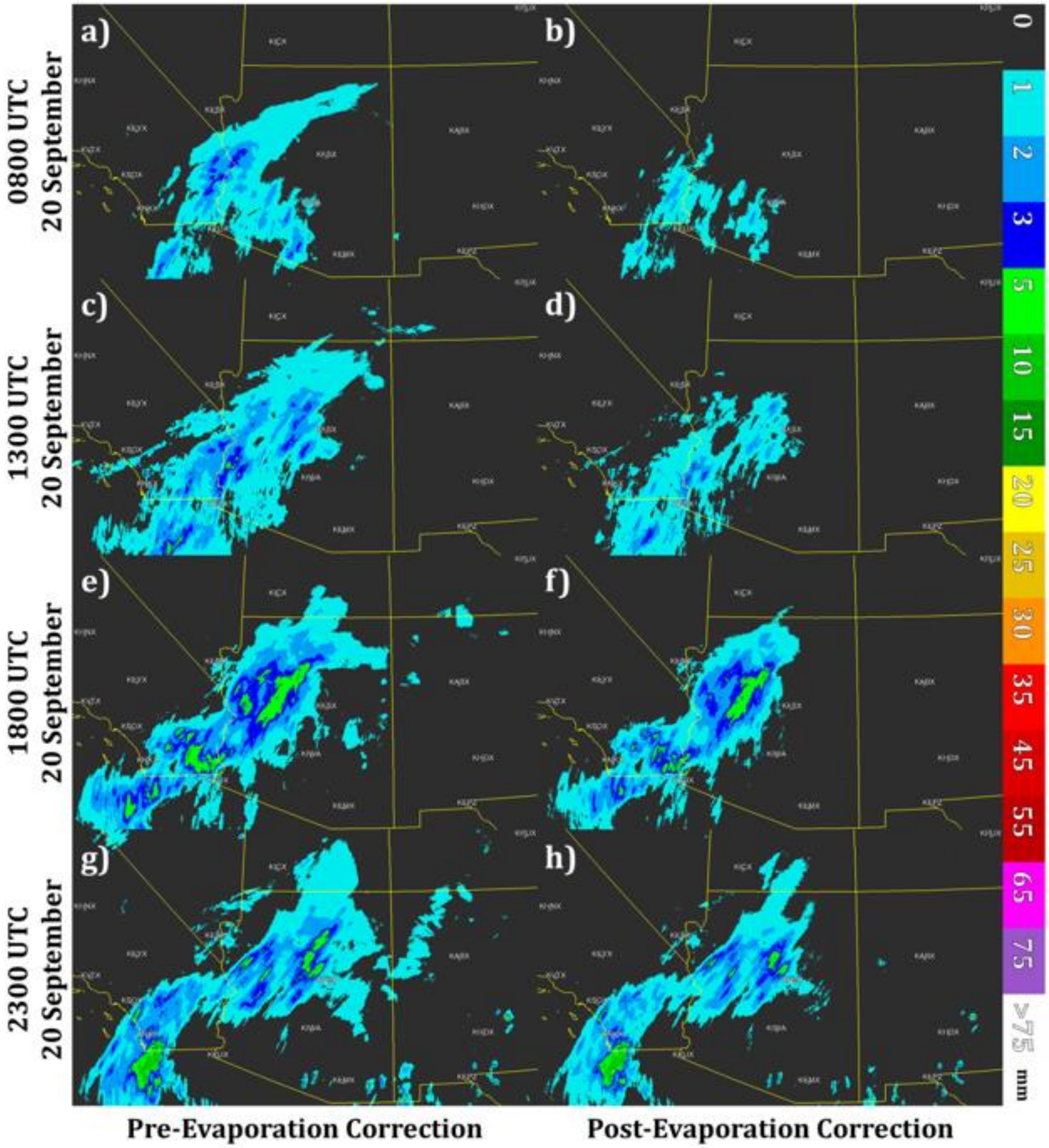
Steven Martinaitis, Carrie Langston, and Youcun Qi (CIMMS at NSSL), Jian Zhang and Kenneth Howard (NSSL), and Heather Grams (ROC)

Multiple limitations still exist with radar sampling and radar-based quantitative precipitation estimation (QPE) that present challenges in creating accurate surface precipitation estimates. One such set of challenges is the overestimation of precipitation and false light precipitation echoes in sub-saturated environments. This is because the precipitation sampled aloft at the radar beam can be greatly reduced or even completed evaporated by the time it reaches the surface. An evaporation correction technique is being developed for the Multi-Radar Multi-Sensor (MRMS) system to help mitigate the impact of evaporation on precipitation between the radar beam level and the surface.

The evaporation scheme is based on the derivations by Gregory (1995), which originated from the theory of evaporation of a water droplet or ice particle through the rate of mass diffusion with respect to time and simplified to a change of rate with respect to height. Two different set of calculations are available for rain and snow.

The evaporation correction scheme was developed using Rapid Refresh (RAP) model data to determine the precipitation type at the surface and to generate a three-dimensional profile of atmospheric conditions to modify the precipitation rate with respect to height. The different calculations for rain and snow are applied throughout the 3D vertical column of each grid cell based upon the height of the freezing level and the lowest altitude of available radar data used to generate the instantaneous precipitation rate. The evaporation correction scheme was tested through a number of case studies to verify how it would improve precipitation biases, remove false light precipitation, and improve gauge quality control with respect to the misclassification of false zero gauge observations.

Overall results showed that the overestimation bias was reduced by 57–76% for rain events and 42–49% for snow events. The number of gauges that were labeled as “false zero” observations through the MRMS gauge QC algorithm were reduced by 52% and 38% for rain and snow events, respectively. This would mean that these gauges are now reported as accurate zero observations and used to shape downstream gauge-influenced products in MRMS. More importantly, the use of a 10 km horizontal resolution RAP data along with the simplified equations provided an optimum run-time of 6–7 s for the evaporation correction scheme, allowing it to run in real-time for MRMS. This project is complete.



Hourly MRMS radar-only QPE accumulations pre-evaporation correction (left column) and post-evaporation correction (right column) for a southwest rainfall event during the following times: (a),(b) 0800 UTC, (c),(d) 1300 UTC, (e),(f) 1800 UTC, and (g),(h) 2300 UTC 20 September.

10. Evaluating MRMS Quantitative Precipitation Estimates versus Single Source Radar QPE Products for the 2014 Warm Season

Stephen Cocks, Steven Martinaitis, and Youcun Qi (CIMMS at NSSL)

A systematic evaluation of MRMS QPE performance across the CONUS during the 2014 warm season was started during FY15 for five regions east of the Rocky Mountains: a) the Southern plains, b) the Southeast, c) the Northeast, d) the Great Lakes/Midwest, and e) and Northern and Central Plains. The study included precipitation events from 59 calendar days affecting 55 radars. Data was collected with reference to single radars to highlight the advantages of a mosaic versus single radar QPE. The chief results were MRMS QPE did better overall than Dual Pol and PPS but it also exhibited a wet bias in the Northern US east of the Rockies. A scheme was developed and implemented to mitigate this impact and is currently running in the operational MRMS QPE. This project is complete.

Publications

Cocks, S. B., J. Zhang, S. M. Martinaitis, Y. Qi, B. Kaney, and K. Howard, 2017: MRMS QPE performance East of the Rockies during the 2014 Warm Season. *Journal of Hydrometeorology*, **18**, 761-775.

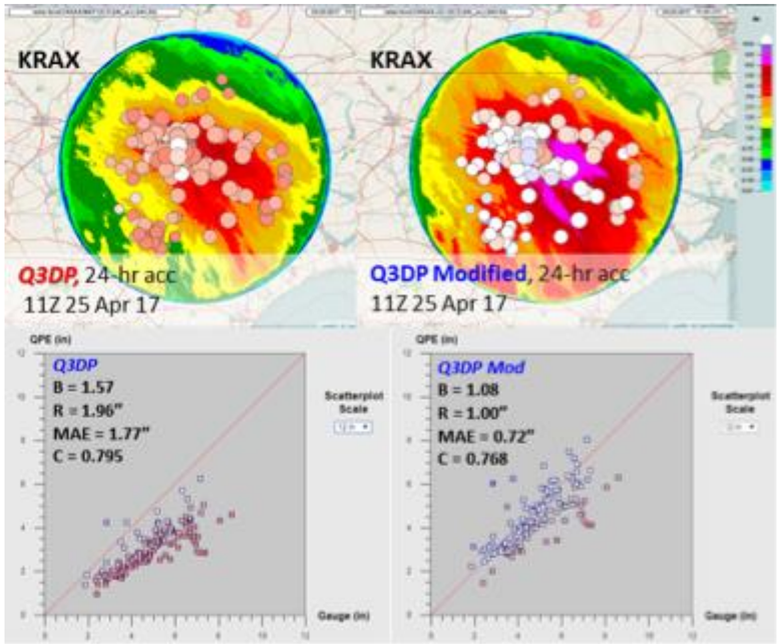
11. Development and Verification of New QPE Algorithm to Estimate Rainfall

Stephen Cocks, Lin Tang, Yadong Wang, and Pengfei Zhang (CIMMS at NSSL)

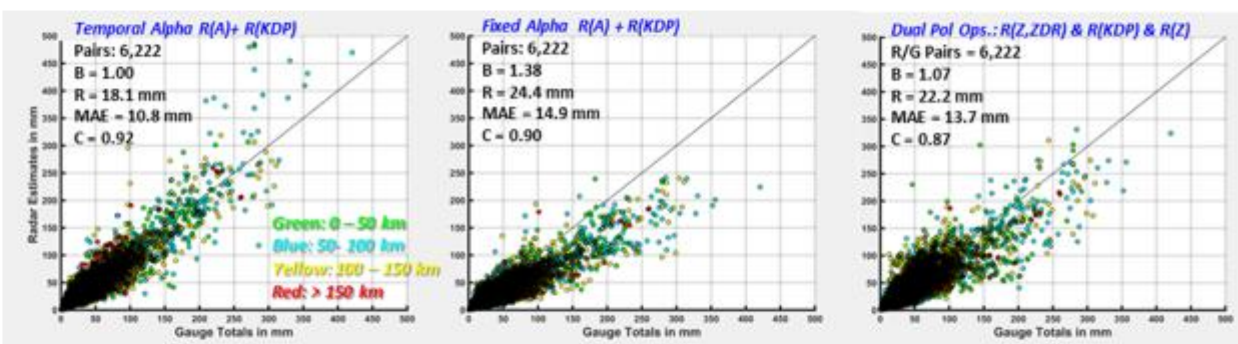
Work continued in developing a new algorithm to estimate rainfall below the melting layer (e.g., pure rain) that performs well under a variety of drop size distribution changes within a precipitation system. The algorithm uses a parameter called specific attenuation, R(A), to estimate precipitation in pure rain and specific differential phase whenever hail is likely present (generally when reflectivity is greater than 50 dBZ). Key to specific attenuation estimates of precipitation was a parameter called alpha which was nothing more than the ratio between the path integrated attenuation (caused by the presence of water droplets) and the specific differential phase along a given radar radial. Since July 2016, a number of improvements were made to the prototype $R(A)+R(K_{DP})$ algorithm: 1) the removal of a logic flaw that caused alpha values to register too high, 2) improved quality control of the PhiDP fields which are critical to the estimation of PhiDP span along a radial, and 3) the implementation of logic to check for cases where rainfall is primarily stratiform in order to apply a more representative alpha value. In the fall of 2016, the algorithm was integrated into MRMS and is currently running in the real-time MRMS testbed system. Testing and evaluation continues as we find new challenges to solve.

Furthermore, CIMMS scientists started evaluating cases where the melting layer was determined via numerical model sounding data rather than determined manually via RhoHV. Similar to what was done a year ago, the updated $R(A)+R(K_{DP})$ algorithm was re-evaluated for QPE generated using a spatially and temporally fixed alpha [fixed R(A)] vs QPE derived using a temporally variable/spatially fixed alpha [temporal R(A)]. These

QPEs were, in turn, compared to the operational Dual Pol data. As before, the temporal R(A)+R(K_{DP}) data exhibited the best results with significantly less error and bias than both Dual Pol and the fixed R(A)+R(K_{DP}) QPE. This project is ongoing.



Comparison of real-time (left column) MRMS Dual Pol QPE (Q3DP) to that with modified code (right column) that better handles heavy stratiform rain events. Data is from the KRAX radar for the 24-hr period ending 1100 UTC 25 April 2017. The top two images are the 24-hr QPE with bias bubbles superimposed, and the bottom two images are the scatter plots of radar QPE (y-axis) versus quality controlled gauges (x-axis).



Comparison of 24-hr R(A)+R(K_{DP}) using a time varying (temporal) alpha (left), R(A)+R(K_{DP}) with alpha fixed at 0.015 (middle) and operational Dual Pol QPE (right). 'B' refers to gauge to radar bias where underestimates are < 1.0, 'R' refers to Root Mean Square Error, 'MAE' is Mean Absolute Error and 'C' is correlation coefficient. The data is from 37 WSR-88D radars for 56 calendar days.

12. Evaluating MRMS Operational Dual Pol Quantitative Precipitation Estimates from April 2017 – March 2018

Stephen Cocks, Steven Martinaitis, Carrie Langston, and Brian Kaney (CIMMS at NSSL)

Per a Radar Operations Center (ROC) MOU tasking, a systematic evaluation of the operational Dual Pol QPE is currently being conducted. The purpose is to compare the Dual Pol QPE to the legacy Precipitation Processing System (PPS) QPE still available in operations to determine if the latter could be pulled from operations. Special instructions were given to extract PPS QPE in a resolution similar to what's typically used by field forecasters. This required our group to use QPE Difference (Dual Pol – PPS) and the operational Dual Pol QPE products to extract the PPS QPE via a newly written computer algorithm. Data will be collected across the CONUS, which will be divided into eight geographical regions in order to determine performance by region. We will also stratify the collected QPE data via the use of ROC estimates of differential reflectivity (Z_{DR}) bias and the use of our Radar Reflectivity (Z) Cross Section Tool (RRCT) to determine the impacts that Z and Z_{DR} mis-calibration had on the operational QPE. Finally, we were asked to compare the Dual Pol QPE to that of the new mosaicked MRMS Dual Pol QPE and the legacy MRMS Radar Only QPE (Q3RAD).

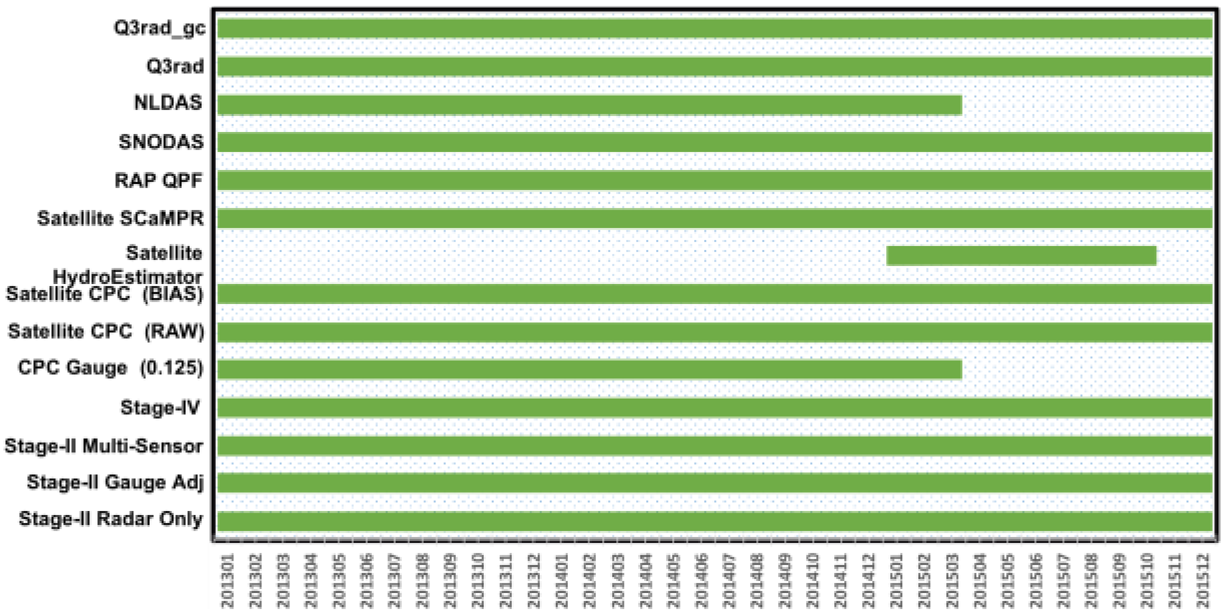
Precipitation events and calibration information were catalogued for cases during April through June 2017. Due to previous commitments, the algorithm needed to extract PPS from the MRMS real-time data feed which could not be finished until July. Hence, we needed to download the Level III products needed to extract the PPS QPE for April through June, as they were previously not archived in order to save computer resources, and store it until the algorithm was ready. Further, the calibration of Z/Z_{DR} was checked for each precipitation event identified for April through June and catalogued into a spreadsheet along with a brief description of the event's characteristics (e.g., was there significant severe weather, MCS, tropical cyclone, etc.). This project is ongoing.

13. MRMS Experimental Testbed for Operational Products (METOP)

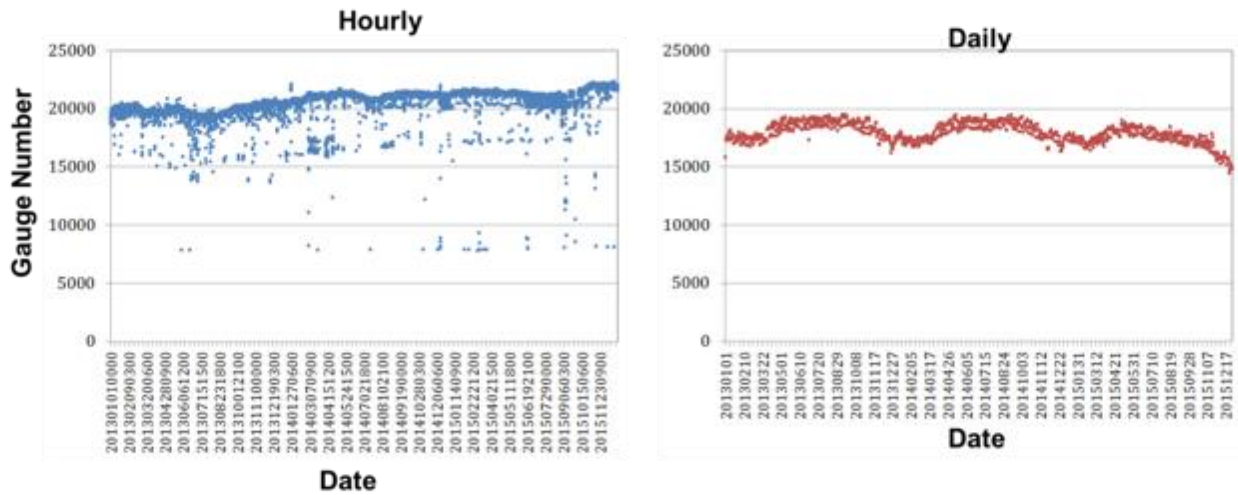
Youcun Qi, Brian Kaney, and Steven Martinaitis (CIMMS at NSSL), Jian Zhang and Ken Howard (NSSL), and Heather Grams (ROC)

Accurate high-resolution quantitative precipitation estimation (QPE) at the continental scale is of critical importance to the nation's weather, water and climate services. To address this need, a Multi-Radar Multi-Sensor (MRMS) system was developed at the National Severe Storms Lab of National Oceanic and Atmospheric Administration that integrates radar, gauge, model, and satellite data and provides a suite of QPE products at 1-km and 2-min resolution.
MRMS system consists of three components: 1) an operational system, 2) a real-time research system, and 3) an archive testbed. The operational system currently provides instantaneous precipitation rate, type and 1-h to 72-h accumulations for conterminous

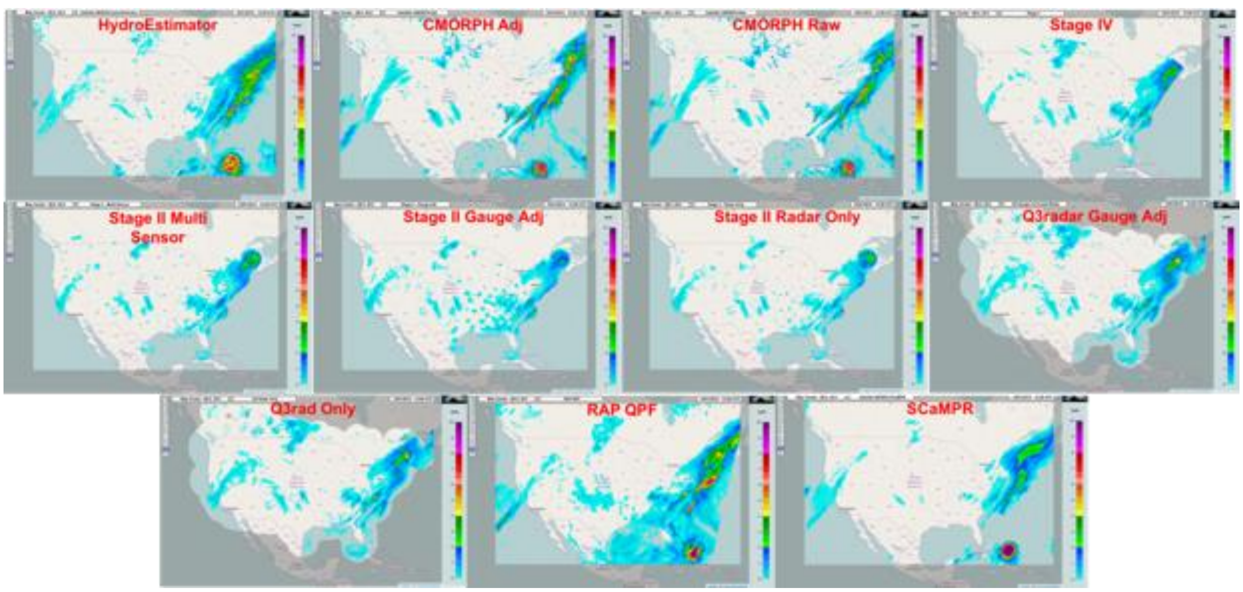
United Stated and southern Canada. The research system has the similar hardware infrastructure and data environment as the operational system, but runs newer and more advanced algorithms. The newer algorithms are tested on the research system for robustness and computational efficiency in a pseudo operational environment before they are transitioned into operations. The archive testbed, also called the MRMS Experimental Testbed for Operational Products (METOP), consists of a large database that encompasses a wide range of hydro-climatological and geographical regimes. METOP is for the testing and refinements of the most advanced radar QPE techniques, which are often developed on specific data from limited times and locations. The archive data includes quality controlled in-situ observations for the validation of the new radar QPE across all seasons and geographic regions. A number of operational QPE products derived from different sensors/models are also included in METOP for the fusion of multiple sources of complementary precipitation information. This project is ongoing.



Data availability of QPE and QPF products with the METOP system.



Hourly (left) and daily (right) gauge observations available in METOP.



Example QPE and QPF products in the METOP system.

14. meteorological Phenomena Identification near the Ground (mPING)

Kim Elmore and Jeff Brogden (CIMMS at NSSL)

The meteorological Phenomena Identification near the Ground (mPING) app has received nearly 1.4 million reports since its beginning on 19 December 2012. The application program interface (API) was included within an app developed by Weather Decision Technology called RadarScope in early 2017. This has increased the number of reports submitted to mPING by about 35% and exposed mPING to nearly 500,000 potential users. The inclusion into RadarScope has also tested the mPING servers, which now must deliver 10-20 GB of mPING data to RadarScope users alone every month. mPING has been submitted to the NWS Capabilities and Requirements

Decision Support (CaRDS) process and is currently in review to establish requirements for NWS operations. This project is ongoing.

15. mPING Random Forest Research

Kim Elmore and John Krause (CIMMS at NSSL)

A random forest was trained on the Rapid Refresh model (RAP) combined forecasts for 6, 12 1nd 18 h lead time pressure-level output from the winter of 2104–2105; cases are labeled with mPING reports collapsed to the four canonical precipitation types of rain, snow, ice pellets, and freezing rain. Only pressure level data are used because RAP output in native vertical coordinates is unavailable. The resulting random forest is then fed RAP forecast output from the winter of 2015–2016 as a test because, according to NCEP, the RAP is unchanged over these two winters. The technique generates four random forests, one for each of from four different wet-bulb (T_w) temperature profiles. The most sensitive profile is the classic “warm nose” profile, where a below-freezing cold layer extends from the surface to a warm (above freezing) layer, which is then topped by below-freezing temperatures. The random forest does best with this profile and, when investigating whether the random forest is sensitive to changes in the NWP model, was the most sensitive to changes.

So far, results have been surprising: even though the RAP NWP model has not changed, there appear to be roughly a 10% difference between predictors generated from the 2014–2015 runs and the 2015–2016 runs. This causes poor performance of the random forest trained in 2014–2015 output. Investigation is continuing to insure that there has not been a software change the intervening time that explains the difference. This project is ongoing.

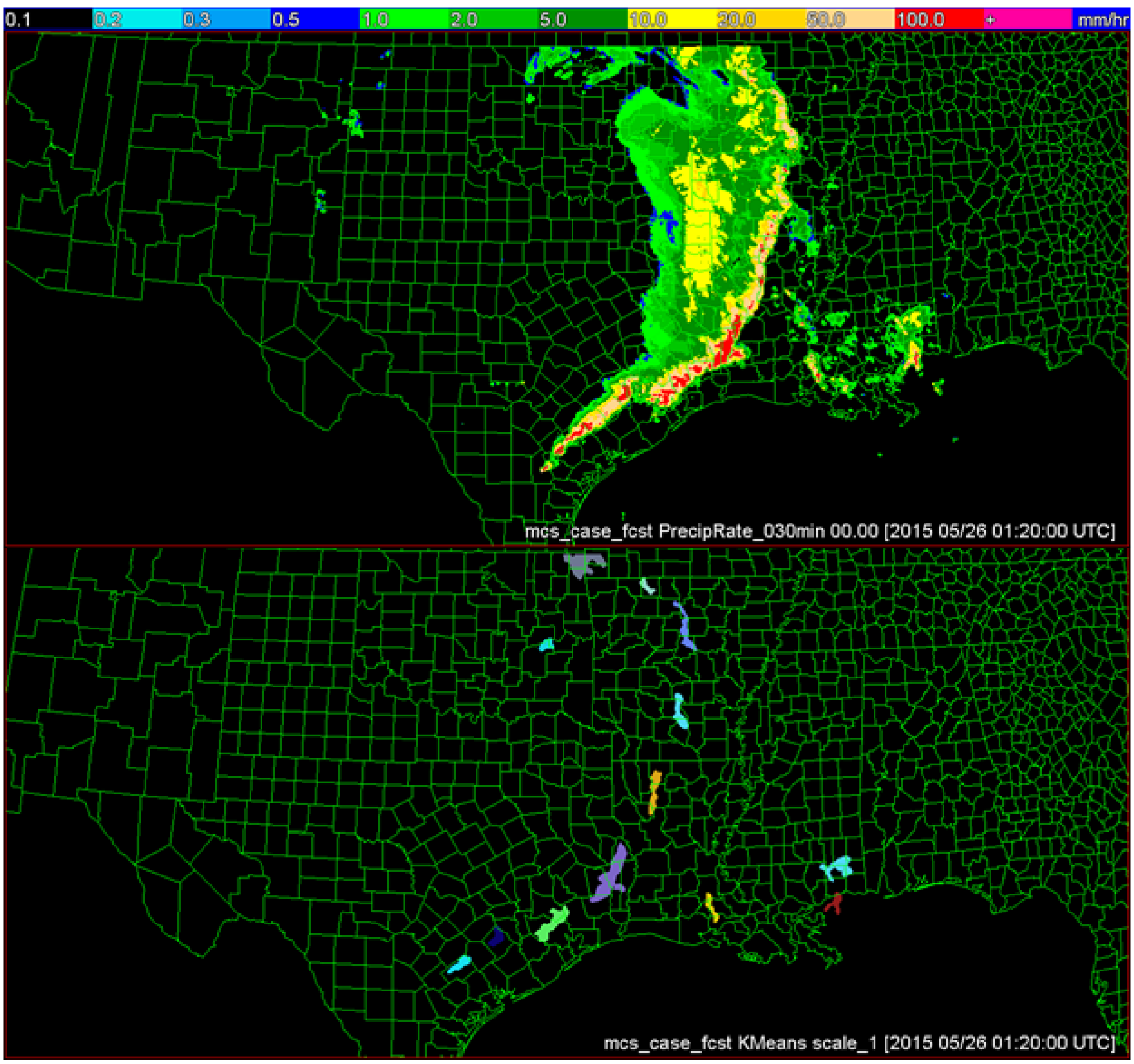
16. Evaluation of a Radar Extrapolation Approach for Very Short-Term QPF

Andrew Osborne and Yadong Wang (CIMMS at NSSL), and Jian Zhang and Kenneth Howard (NSSL)

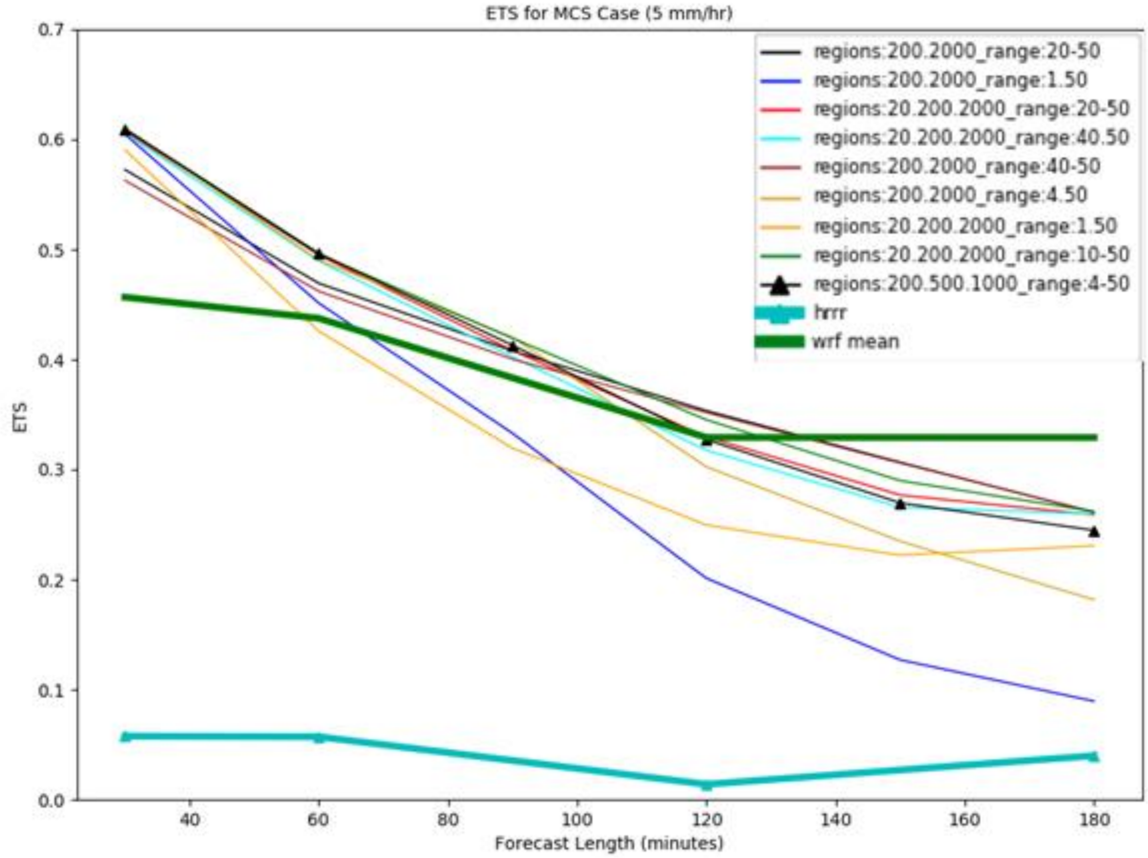
A short-term (0–3 hr) QPF tool which can give accurate forecasts of precipitation at the basin scale allows forecasters to issue flash flood warnings with more confidence at longer lead times. Precipitation forecasts from NWP models are often not reliable in this time frame as they take time to adjust to the initial conditions (so-called “spin up” effects). Another potential QPF approach involves extrapolation of precipitation areas forward in time based on motion estimates from successive images. This type of nowcasting has been shown to be effective when extrapolating reflectivity echoes from storms, but very little research has been done on the feasibility of this approach for real-time precipitation forecasting.

The Warning Decision Support System-Integrated Information (WDSS-II) segmotion algorithm is used here to identify, track, and advect MRMS radar-based QPE fields for three different cases. The experiments showed the forecasts are very sensitive to the

size of identified areas. The better performance came from experiments using parameter settings that resulted in identification of precipitation areas that a human observer would likely recognize as the smallest trackable entities. The segmotion forecasts were compared to model output from the High Resolution Rapid Refresh (HRRR) and the Warn on Forecast Weather Research and Forecasting (WRF) model. Segmotion clearly outperforms the HRRR and is similar in skill to the WRF. The skill of segmotion forecasts drops off substantially with increasing forecast length and the realistic use of this method appears to be in the 0–2 hour range. Several recommendations were made to improve this type of extrapolation method for future operational use. These include directed searching via a background wind field to avoid misassociation of precipitation areas across time frames, use of more meteorological information to be able to better forecast the evolution of the size, shape, and intensity of the precipitation areas, and automatic selection of appropriate area identification parameters based on the scale of features present. This project is complete.



Segmotion 30-minute forecast of precipitation field for MCS case (top) and identified precipitation areas for one of the better performing experiments for this case (bottom).



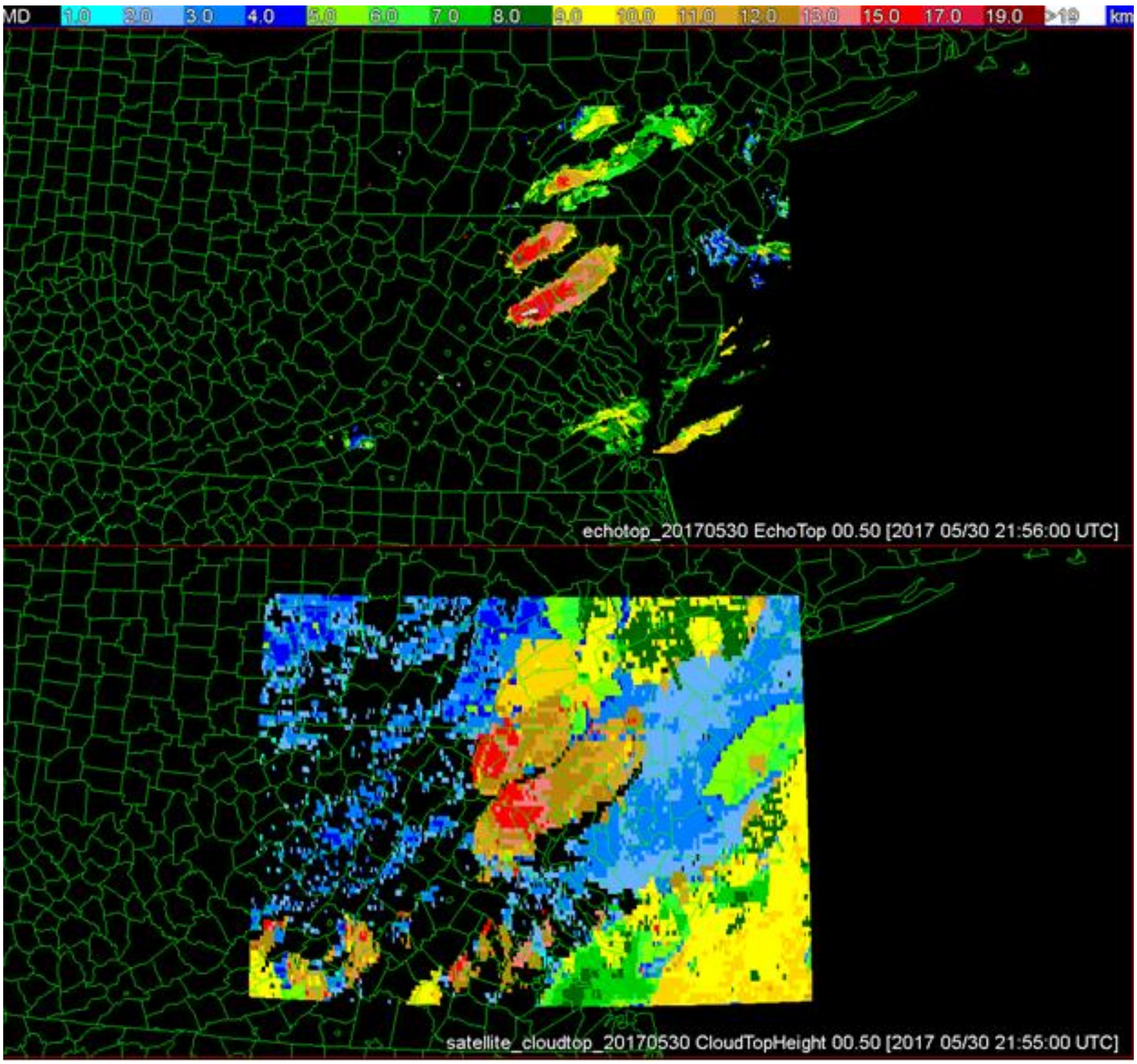
0-3 hour Equitable Threat Score (ETS) plotted for several segmotion experiments as well as the HRRR and WRF model QPFs for an MCS case using a rain rate threshold of 5 mm hr^{-1}.

17. MRMS Support for Cloud Detection Algorithm

Andrew Osborne, Lin Tang, Stephen Cocks, and Valery Melnikov (CIMMS at NSSL), and Jian Zhang (NSSL)

An automated, radar-based algorithm capable of detecting cloud boundaries would be useful for aviation and radiation/climate applications. It is necessary to use the existing national WSR-88D radar network to develop this type of method for potential real-time use on a CONUS-wide scale. While the WSR-88D radars were not built specifically for cloud detection, they do have the necessary sensitivity to detect some non-precipitating clouds. Based on suggestions from Melnikov et al. (2016), a cloud top product is being generated in the MRMS system. This product uses the merged 3D reflectivity mosaic to find the highest grid point with non-zero reflectivity for each vertical column. For cases representing a variety of weather conditions, the MRMS product is being evaluated against GOES satellite cloud top height measurements.

Preliminary results indicate a lack of sensitivity to small cloud droplets beyond about 10 km from the radar. Many of the thinner, non-precipitating cloud areas are assigned a height by the satellite product but are going undetected by the MRMS product. The MRMS product looks to be most effective at detecting non-precipitating clouds when they are on the periphery of precipitation systems (i.e. anvils spreading from convection). There is a weak echo threshold applied to the WSR-88D radar reflectivity as part of the quality control process in the MRMS system. Reduction of this weak echo threshold resulted in a slight increase in detected cloud area in some cases. Further alterations to the initial technique are necessary for the radar-based product to achieve comparable skill to the satellite-based method in representing the observed cloud fields. This project is ongoing.



Cloud top height (km) from MRMS product (top) and from GOES-East satellite product (bottom).

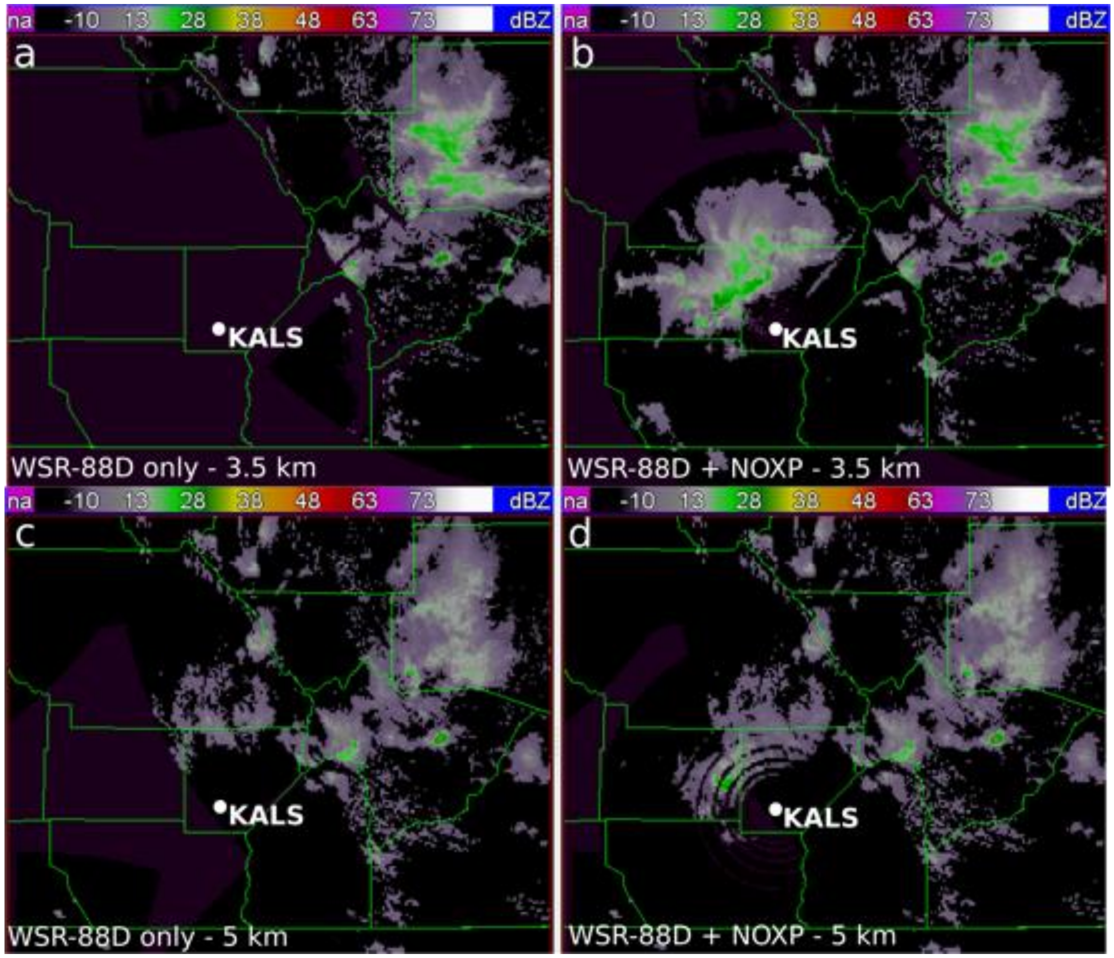
18. Alamosa, CO Mobile Radar Deployment and Analysis

Andrew Rosenow and José Meitín (CIMMS at NSSL), and Kenneth Howard (NSSL)

The current WSR-88D network is insufficient to provide full radar coverage for the United States, especially in regions with complex terrain. This project builds on previous NSSL efforts using mobile radars to demonstrate the potential financial and public safety benefits of gap-filling radars. This deployment, supported by the Colorado Department of Natural Resources and the City and County of Alamosa, happened from December 2016 to April 2017. NSSL personnel operated the mobile radar and performed troubleshooting both remotely and in person. Data were collected for as many events as possible. After the deployment concluded, the data were quality controlled, a task made more difficult due to cold-induced mechanical issues with radar hardware.

Data from the radar deployment were used to test QPE algorithms developed at NSSL by CIMMS scientists. These results and the lessons learned from the deployment this past winter were delivered in the form of a report to the funding agencies. In addition to the results of the observations, the deployment also provided the opportunity for educational outreach. During the radar deployment, NSSL personnel demonstrated radar operations to students from Adams State University with an interest in meteorology.

During the winter, a scientifically significant event was captured by the mobile radar. On 24 January 2017, a snow squall impacted the airport in Alamosa, CO. This event was not forecast ahead of time and was not observed by the operational radar network. Data from this case has been analyzed, and algorithms in the Multi-Radar Multi-Sensor (MRMS) system were used to merge data from the mobile radar with the operational radar network. The result of this merger show both the benefits of gap-filling radars in detecting inclement weather as well as the ability of NSSL's MRMS system to combine gap-filling radars with other operational radars to provide added value to decision makers. This project is ongoing.



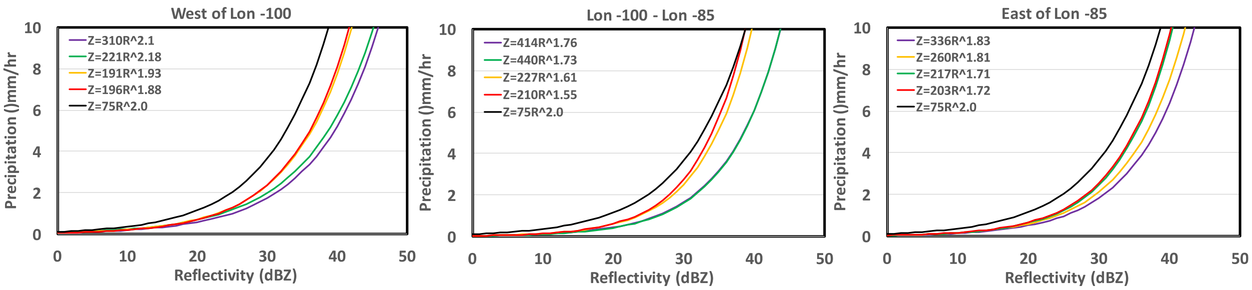
MRMS composite reflectivity at 2030 UTC 24 January 2017. Panels (a) and (c) are for NEXRAD only observations; (b) and (d) add mobile radar observations. Elevations of each composite are as indicated. San Luis Valley Airport (KALS) was the site of the mobile radar.

19. Enhanced Accuracy of Radar Snowfall Estimation with a New Z-S Relationship

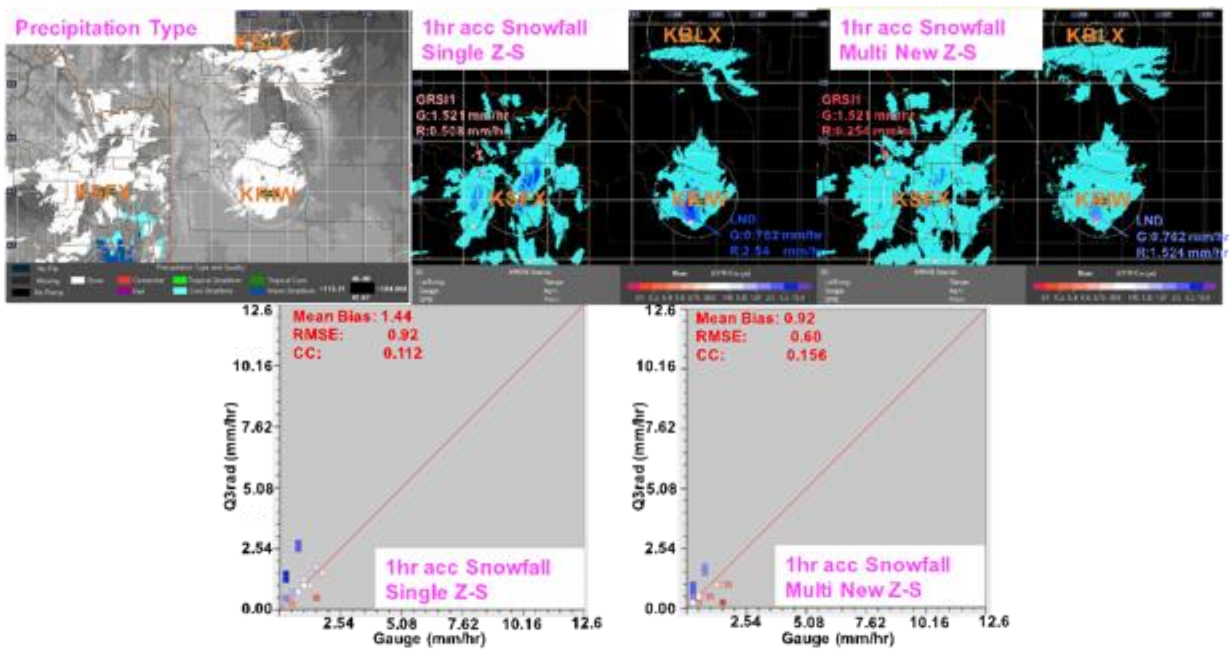
Youcun Qi (CIMMS at NSSL) and Jian Zhang (NSSL)

Snow may have negative effects on roadways and human lives, but the result of the melted snow/ice is good for farming and other water resources. In the Southwest and intermountain West of the United States, water shortage is a very big concern. However, snowfall in the winter can provide humans, animals, and crops an almost unlimited water supply. Using radar to accurately estimate the snowfall is very important for human life and economic development in the water lacking area. The current study plans to analyze the characteristics of the horizontal and vertical variations of dry/wet snow using dual polarimetric radar observations, relative humidity, and in situ snow water equivalent observations from the National Weather Service All Weather Prediction Accumulation Gauges (AWPAG) across the CONUS, and establish the relationships between the reflectivity (Z) and ground snow water equivalent (S). The new Z-S

relationships will be evaluated with independent Community Collaborative Rain, Hail & Snow Network (CoCoRaHS) gauge observations and eventually implemented in the Multi-Radar Multi-Sensor system for improved quantitative precipitation estimation for snow. This project is ongoing.



New derived Z-S relationships for different domains.



(Top left) surface precipitation type, (top middle) 1-h snowfall accumulation with single Z-S relationship, and (top right) 1-h snowfall accumulation with multiple Z-S relationships. Bottom row shows the scatter plots for (low left) single Z-S relationship and (top right) with multiple Z-S relationships.

20. Development of Web-Based Tools and Displays for Real-Time QPE and Hydrologic Analysis

Brian Kaney, Carrie Langston, and Karen Cooper (CIMMS at NSSL)

Within the hydrometeorology group a cornerstone of all research and development has always been the evaluation of experimental products in real-time across the entire CONUS. The primary interfaces for this evaluation are various versions of the QPE

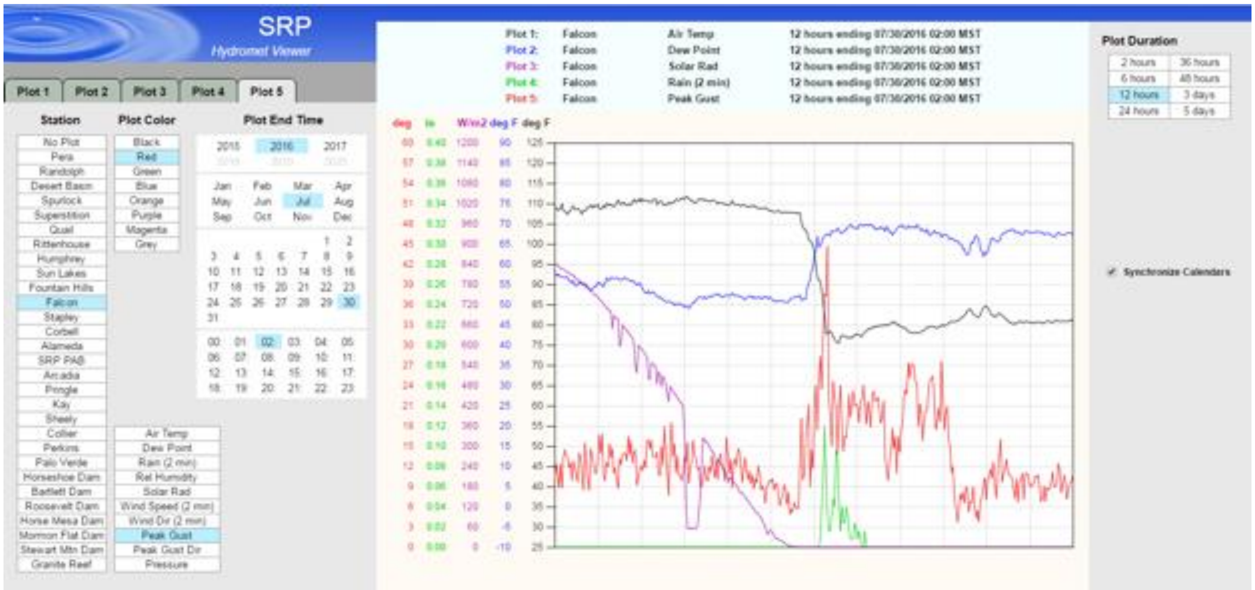
Verification System (QVS; http://vmrms-web.dmz.nssl and https://mrms.nssl.noaa.gov) and the Radar Reflectivity Comparison Tool (RRCT; http://rrct.nwc.ou.edu). Several updates and improvements were made to both systems in FY17. This work is ongoing. A closely allied ongoing project is also the Hydromet Viewer for Salt River Project in Phoenix. Related projects for the Federal Aviation Administration (FAA) and Radar Operations Center (ROC) were also completed.

a. Hydromet Viewer for Salt River Project

The Salt River Project (SRP) water and power utility operate in a very challenging QPE/QPF environment and had the first WSR-88D installation in the mountain west. With significant mountain blockages, complex terrain, large areas of orographically enhanced precipitation, significant winter precipitation from low based clouds, significant summer thunderstorms from high based clouds, and even tropical storm remnants, central Arizona is well suited to test the limits of multi-sensor QPE and the new dual-polarization capabilities in MRMS.

The previous year of this project saw a complete revamping the internal meteorology web tools used by SRP. The latest version of the full MRMS suite was installed and a Hydromet Viewer was built as a one stop suite of tools to monitor weather in real-time, aid in weather related decision-making and facilitate post analysis. In the current year a significant round of improvements and additional tasking was completed. There were many small incremental changes in display options and user requests but also a couple of completely new tool capabilities. One of these involved a web tool that displayed, in one place, a wide variety of NWS and SRP text weather products. This replaced an existing capability but with the significant addition of saving a long term archive for use in post analysis.

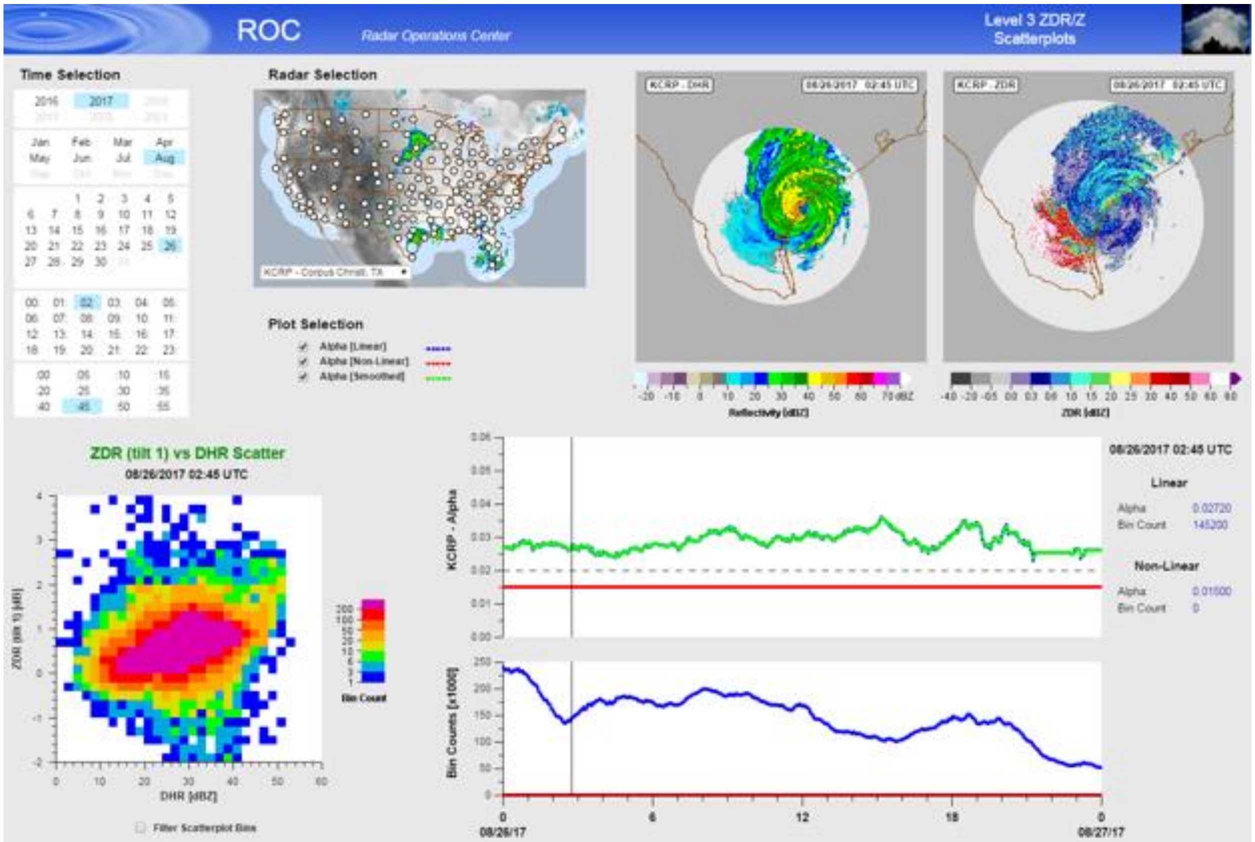
The single biggest new web page was a major line trend plotting tool. SRP has a network of automated surface weather stations (PRISMS) monitoring several weather variables at high spatial and temporal resolution. The long term archive of this data provides a highly valuable resource for many types of post analysis. The line trend tool was designed to allow very general comparison plotting in this dataset. Up to five plots can be created at once. These plots could use several different stations and/or several different sensor variables and/or several different time periods. One could look at a stack of five 24-h temperature curves for the same station for different days. One could look at temperature and dew point for two different stations during an outflow event.



Sample image from of the Line Trend Tool for Salt River Project Hydromet Viewer showing five different mesonet sensor variables for the same station and 12 hour period.

b. Z_{DR}/Z Scatterplot Display for the Radar Operations Center

Our group maintains a suite of tools for the ROC looking at Level 3 single radar metadata. One major new tool was added this year. This tool was a complex undertaking as it brought together in one place data from a variety of sources and using a variety of techniques. Scatterplots were desired for the dual pol differential reflectivity variable (Z_{DR}) versus the reflectivity (Z) for each NEXRAD site at any arbitrary time in our archive. The Hydrometeor classification product was also read as the scatterplot is only supposed to cover those regions with liquid hydrometeors. The work is intended as a real time testbed for the evaluation of a rain rate determination method pioneered in the literature by Ryzhkov and Zrnic in the 1990's. A central segment of the Z_{DR} versus Z plot is fit with a straight line with a slope referred to as alpha. The alpha parameter is then used to determine the Z-R relation to find rain rates. The web tool has instantaneous plots of alpha (and the number of scatter bins available) via a couple of different methods.



Sample image from Z_{DR}/Z Scatterplot and Alpha plot web tool created for the Radar Operations Center.

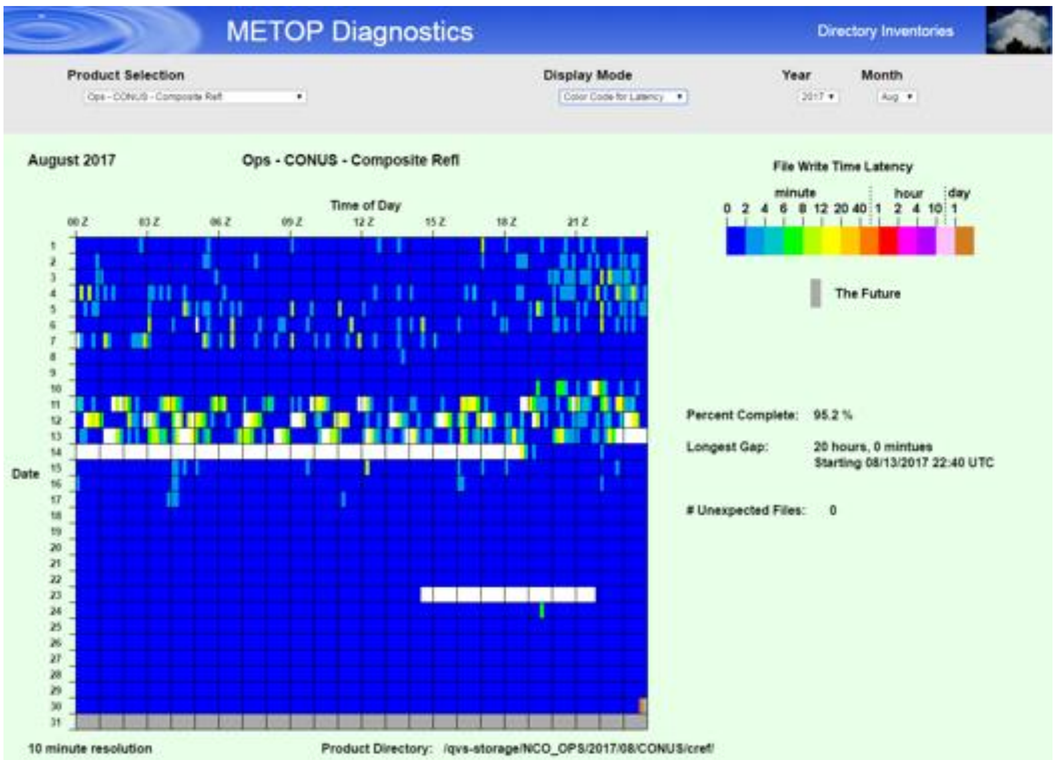
c. QVS work for VMRMS System Hosted in Norman and Operational Data at NCO

The QVS acronym originally came from QPE Verification System, where QPE itself stands for Quantitative Precipitation Estimate. Evaluating our precipitation products against other fields and ground truth is still a core purpose of the QVS. But as our methods for creating a precipitation field relies on many inputs there are also many variables, fields, and observations that can be brought to bear on post analysis. As such the term QVS has been used for a wide variety of web tools that aid our analyses in many different ways.

The Multi-Radar Multiple-Sensor (MRMS) product suite that went into operations in the previous fiscal year still has a research version running locally in Norman. In FY17, a major reorganization of this MRMS system occurred. One major aspect was that the MRMS system, and the attendant web tools, was moved from ou.edu domain machines to nssl.noaa.gov domain machines. This was a major undertaking that was active for much of the current year. Much reorganization and installation was involved. Numerous web tool diagnostics were added or modified.

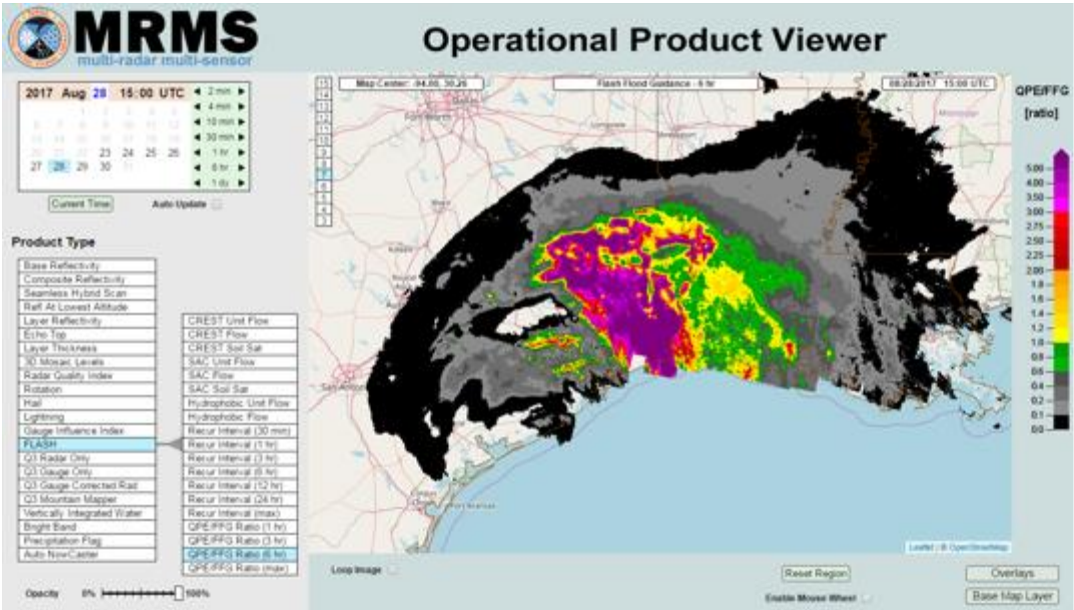
One new diagnostic was an inventory web tool. An image of the inventory for any one of several hundred products can be quickly and easily obtained. The inventory is in the

form of a dense graphic that allows assessment of the full two minute resolution over an entire month at a time at a quick glance. Besides just showing whether a file was created or not, the imagery can also be color coded to show file size (unexpectedly small or large files in a sequence can signal a variety of problems) or color coded to show file time stamp latency (how long after real time it took to generate and write out a given file).



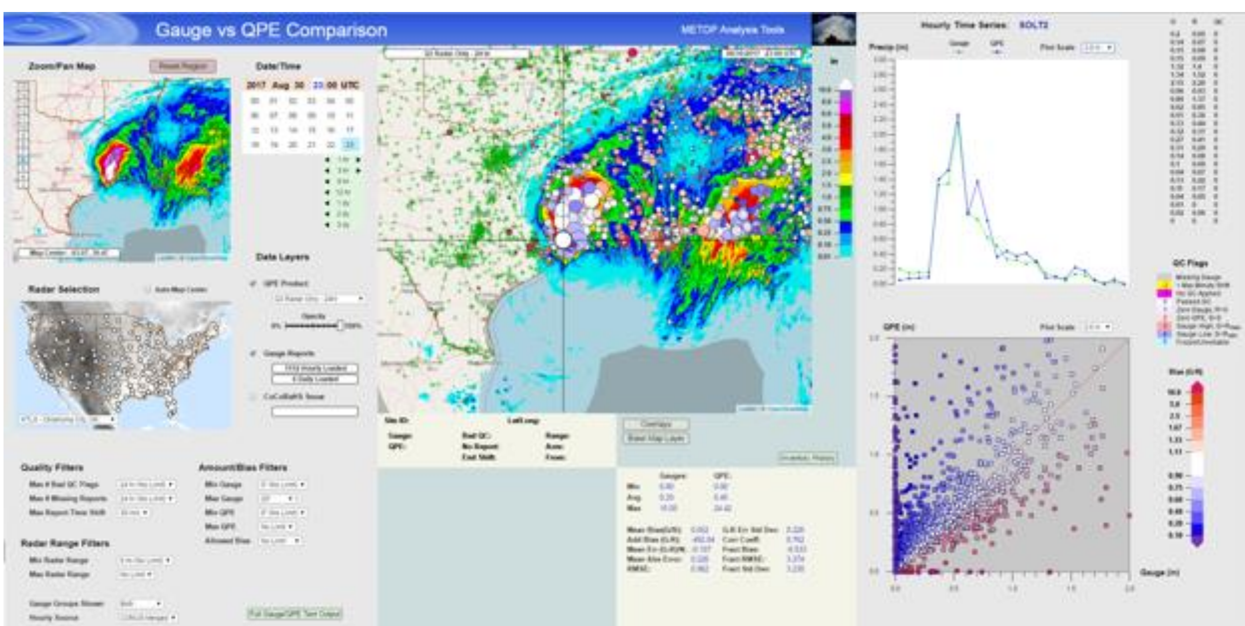
Sample inventory tool for MRMS composite reflectivity.

For many years, our group has provided public access to product viewers and basic analysis tools for our product suite. This was missing for a time during the domain move this year. Recently a new public facing web tool called the Operational Product Viewer was developed and deployed. This page has the largest variety of products available of any generation of viewer. Previous viewers have focused primarily on the suites developed by the Hydro group, but to this was added the full MRMS suite including all the severe weather products, AutoNowcaster, and FLASH.



Sample image from the publically available Operational Product Viewer.

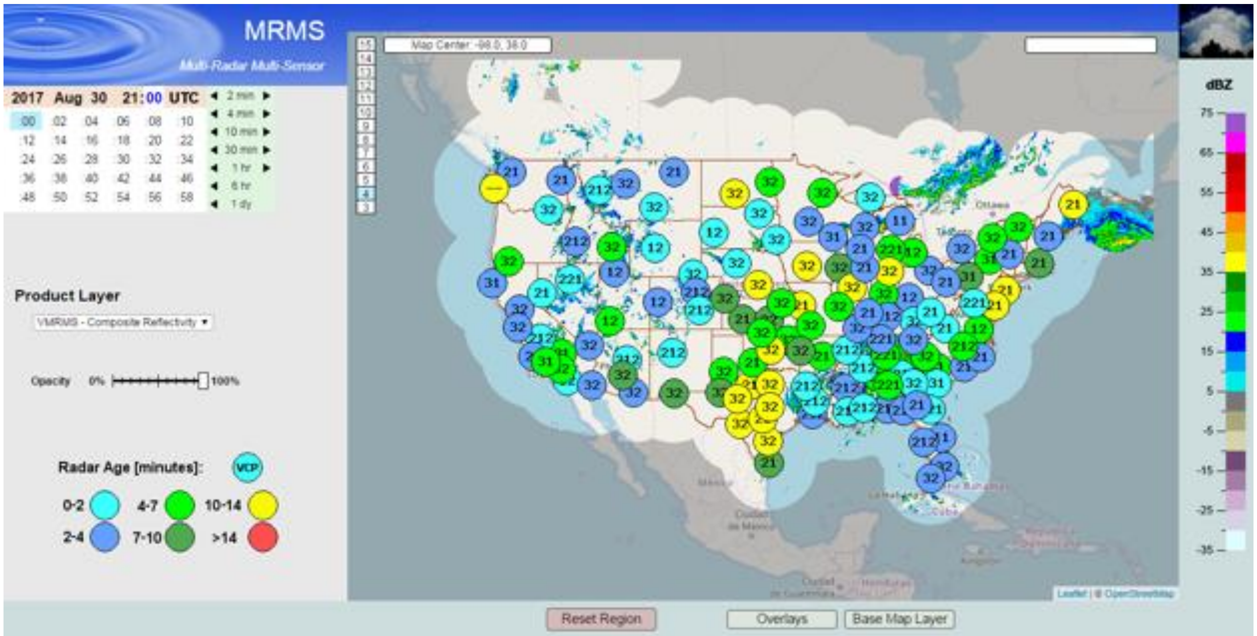
Our local research version of the MRMS also has many web tools that are not available outside of the lab network. A significant web tool developed for use internally is the Gauge vs. QPE Comparison Tool. It bears some similarity with a tool from a previous year but the back end has been redone to address some serious performance issues and some important new features were added. This tool allows rapid comparison of hundreds of hourly QPE traces with hourly gauges via a simple mouse hover. Gauges can be manually quality controlled as well.



Sample image from the Gauge vs QPE Comparison Tool.

d. QVS Work for the FFA

A QVS type tool was created for the FFA called the Time Stamp Mosaic. This display shows a map of the NEXRAD network showing the VCP of each radar and color coded for the age of the last volume scan used in the 3D MRMS reflectivity mosaic. This project is ongoing.



Sample image from Time Stamp Mosaic viewer for the FFA.

CIMMS Task III Project – ARRC Demonstrator Development Activities for the MPAR Program: HORUS and CPPAR

NOAA Technical Lead: Kurt Hondl (NSSL)

NOAA Strategic Goal 2 – *Weather Ready Nation: Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Task III

1. HORUS

Robert Palmer, Hjalti Sigmarsson, Jorge Salazar, Caleb Fulton, Nafati Aboserwal, Jose Diaz, and Javier Ortiz (ARRC)

Objectives

This project's goal is to develop a mobile all-digital, S-band, dual polarization radar demonstrator with 1024 elements to serve as a weather radar research testbed, a technology demonstrator, and, most importantly, as a tool to mitigate a number of

remaining fundamental challenges towards the implementation of a national surveillance radar that is capable of satisfying both current scientific and operational needs as well as future requirements through digital upgrades. In particular, the integration, control, and beamforming challenges associated with a very large number of low-cost transceiver channels (even if not element-level digital) remains a risk, as does polarimetric and in-situ array calibration, maintenance and upgrade-related concerns, and interference-related threats.

In addition to making progress towards the procurement of a truck for the mobile demonstrator, the primary objective for this last year has been working towards the development of a Line Replaceable Unit (LRU), an 8x8-element subarray building block of transceiver and front-end electronics that will make up the larger 4x4 LRU demonstrator. As a major portion of the LRU effort, the team has also been developing a high-performance antenna array of 8x8 elements for a weather phased array antennas. Mismatch between co-polar patterns (for H- and V-polarization) below 0.1 dB and cross-polar isolation below -40 dB across an AZ scanning range between -45 to 45 degrees is defined as the main objectives for this task. The radiating element was designed using the combination of an aperture-coupled feeding technique with a novel cross-stacked patch antenna that offers high port isolation (<-50 dB), small spurious radiation, and low impact of excited higher order modes.

Accomplishments

The following is a summary of the accomplishments over the reporting period, as depicted in the two figures below.

a. Truck Procurement and Integration

The truck has been purchased for the mobile demonstrator, and initial mechanical designs are complete for the positioners, outriggers, cooling system, and housings. The 80 kW power take-off (PTO) generator is also soon to be integrated.

b. LRU and OctoBlade Progress Summary (see first figure below)

- The "see-through" liquid cooling prototype of the LRU has been fabricated and has successfully shown that the chosen solution is robust to OctoBlade swaps and provides even distribution of cooling functions; a semi-final mechanical design is currently being prototyped in aluminum
- Initial synchronization of multiple AD9371 chips has been achieved on OU PCBs, with continued progress towards robustness and optimization
- Chip-to-chip communication between control (Cyclone V) and processing (Arria 10) FPGAs over custom adaptor boards has been demonstrated
- The second FEM design has been tested, and a design has been completed for biasing and triggering
- A four-channel "benchtop" but physically- and electrically-representative testbed has been used for initial waveform loopback-based testing between channels, to individually debug and develop transmitter and receiver functionality

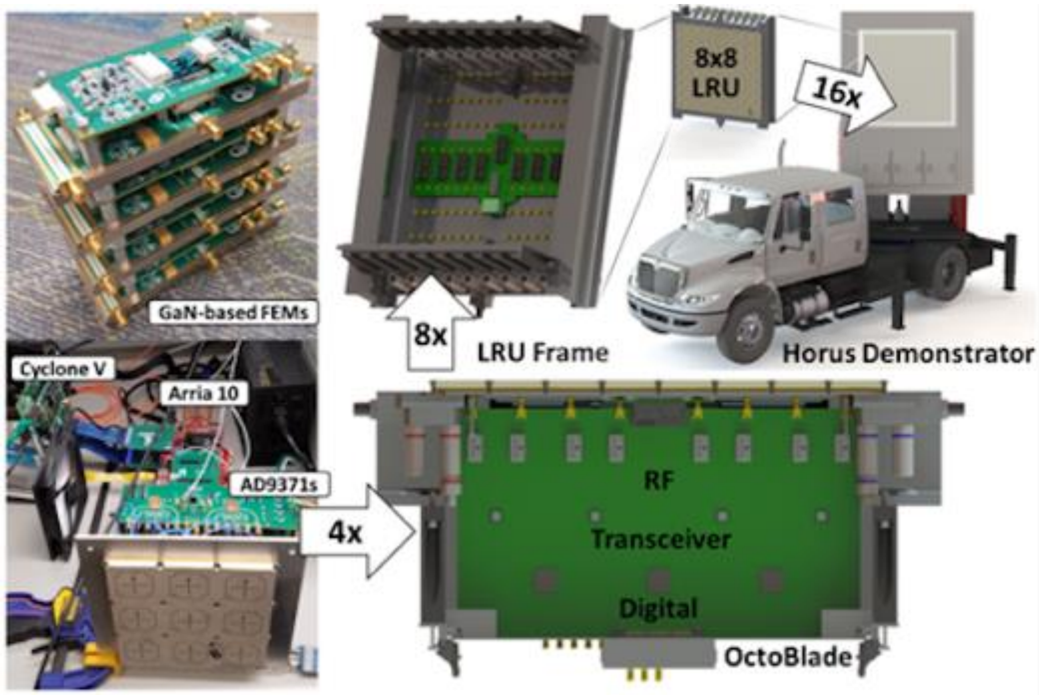
- FPGA firmware has been developed for generating FEM timing and pulsing/triggering signals
- A transmit waveform generator has been developed, capable of LFM, NLFM, and arbitrary waveforms
- A multi-channel channelizer has been developed for receive operation to separate out multiple sub-bands/functions
- The team has made progress towards practical implementation of I/Q calibration and mitigation or understanding of other spurious products, on both transmit and receive.
- A GUI for viewing and analyzing waveforms has been developed and used for debugging and development purposes
- Initial LO synchronization testing and planning for the overall distribution/locking scheme has begun; this will inform the final scheme for the 1024-element demonstrator
- Careful planning for on-line calibration has been done, resulting in a slight design change in the FEM to support a wider dynamic range of mutual coupling values that will be useful for these algorithms
- A sub-contractor has been working towards a packetization protocol for use in DBF between OctoBlades over RapidIO
- A hardware prototype RapidIO link prototype has been established, with data moving over it (importantly, including DMA transfers)

c. Antenna Array Development

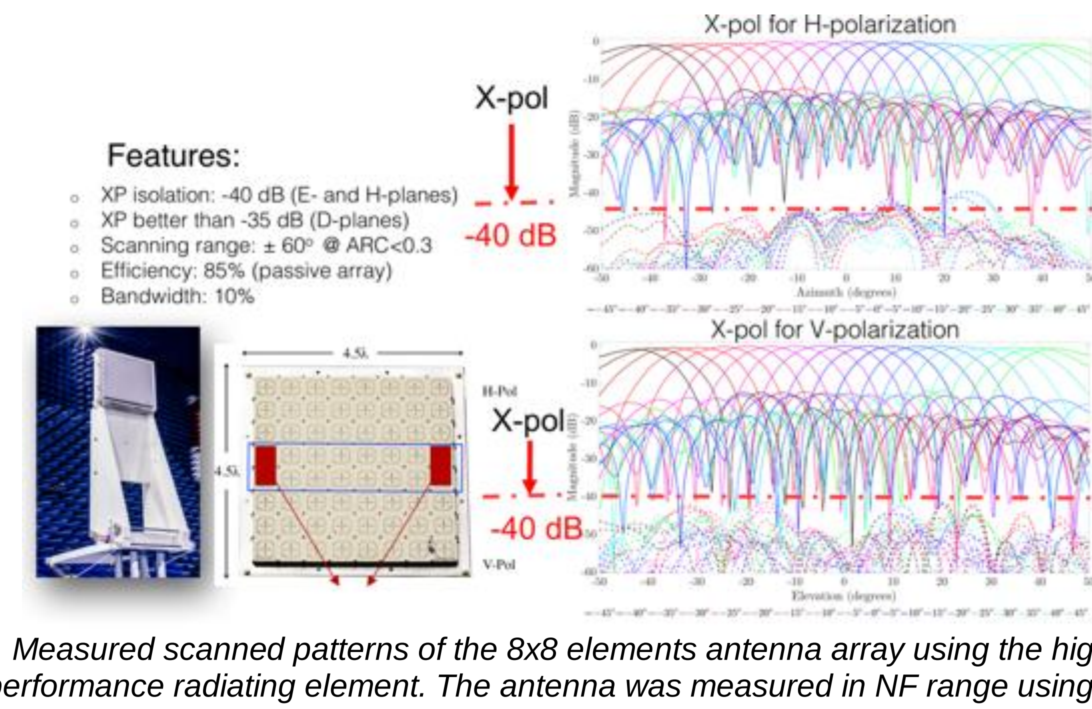
Two antenna array prototypes of 3x3 elements and 8x8 elements were designed, fabricated, and characterized in the ARRC near field and far field range system. The design included two new design features that mitigate spurious radiations, especially due to the internal and external asymmetric diffracted fields in the array. To characterize the effect of diffracted fields in the antenna patterns as functions of the gaps and array size, a customized 6-axis robotic RF scanner currently under development will be used. The robotic RF scanner is a state-of-the-art RF system that enables high precision RF characterization of features up to 100 μm.

The second figure below illustrates the results of scanned array antenna patterns scanned in the E and H-planes for H and V-polarization. To obtain the scanned patterns the design and fabrication of a 16 channel analog beamformer was integrated with the 8x8 antenna array.

Finally, significant progress has been made towards the potential inclusion of a static filter in the new version of the antenna; this is documented by Dr. Sigmarsson in the relevant section of this report.



Progress towards the development of an LRU for the Horus Demonstrator. Top left: Gan-based front-end modules, with prototype biasing and triggering circuitry. Bottom left: low-power 4-channel test setup for digital transceivers and FPGA interfaces to them, with a small test antenna being used to provide waveform feedback through mutual coupling.



Measured scanned patterns of the 8x8 elements antenna array using the high performance radiating element. The antenna was measured in NF range using 16 channel TR modules. Cross-polarization below -38 dB for H-pol and below -40 dB for V-pol was obtained.

2. CPPAR

Andrew Byrd, Caleb Fulton, and Robert Palmer, Shajid Islam, Yan (Rockee) Zhang, and Guifu Zhang (ARRC), and Dusan Zrnic and Richard Doviak (NSSL)

A summary of activities on CPPAR observational studies is available elsewhere, in the report, “First Weather Observations with the CPPAR Demonstrator: Internal Technical Report”. See the ARRC principal investigators.

Theme 2 – Stormscale and Mesoscale Modeling Research and Development

NSSL Project 3 – Numerical Modeling and Data Assimilation

NOAA Technical Leads: Jack Kain, Adam Clark, Pamela Heinselman, Don MacGorman, Ted Mansell, Lou Wicker, and Conrad Ziegler (NSSL)

NOAA Strategic Goal 2 – *Weather-Ready Nation – Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Task II

Overall Objectives
Develop and test numerical weather prediction models, data assimilation techniques, and diagnostic, visualization, and verification methods to improve severe weather forecasts.

Accomplishments

1. Visualization of NEWS-e Output through Redesign of the NEWS-e Forecast Viewer

Jessica Choate and Patrick Skinner (CIMMS at NSSL)

Forecaster input in real-time simulations is invaluable in the transition from research to operation of the NEWS-e system. Through work with the Norman WFO and 2017 HWT participants, I redesigned the NEWS-e Forecast Viewer to align more so with the vision and goals of NEWS-e compared to the original viewer. Products have been redesigned to increase understanding and usability. The forecast viewer has been restructured to highlight NEWS-e's unique benefits that elevate the forecaster experience while interacting with NEWS-e forecasts products. I also designed two member viewers to accommodate the unique structure of NEWS-e output and high demand for individual member plots from forecasters and researchers. I also led efforts to design website help products including help images for each product and tutorial videos.

2. First Demonstration of the NSSL Experimental Warn-on-Forecast System as part of the 2017 Spring Experiment

Jessica Choate and Patrick Skinner (CIMMS at NSSL), and Adam Clark, Pamela Heinselman, and David Imy (NSSL)

With the aim of providing useful forecast guidance between the issuance of watches and warnings, NEWS-e's use in this capacity was explored within the NOAA Hazardous Weather Testbed (HWT) for the first time during the 2017 Spring Experiment. The primary goals of this part of the experiment were to explore how short-term ensemble forecast guidance from NEWS-e could be used by an expert forecaster to produce a

series of 1-hour severe weather outlooks, and observe how the forecaster's understanding, use, and attitudes about NEWS-e guidance evolved through the experiment. Each morning, verification was performed by comparing to the "practically perfect" outlooks created after the outlook period.

This aspect of the experiment had participants use the NEWS-e 1900 UTC forecast to create 21-22 UTC and 22-23 UTC severe weather outlooks and then update those outlooks based on the 2000 UTC forecast. Notes were taken every operational day throughout the experiment on forecaster impressions, struggles, and usability of NEWS-e output. Preliminary results are in progress and an abstract has been submitted for the 2018 AMS Annual Meeting.

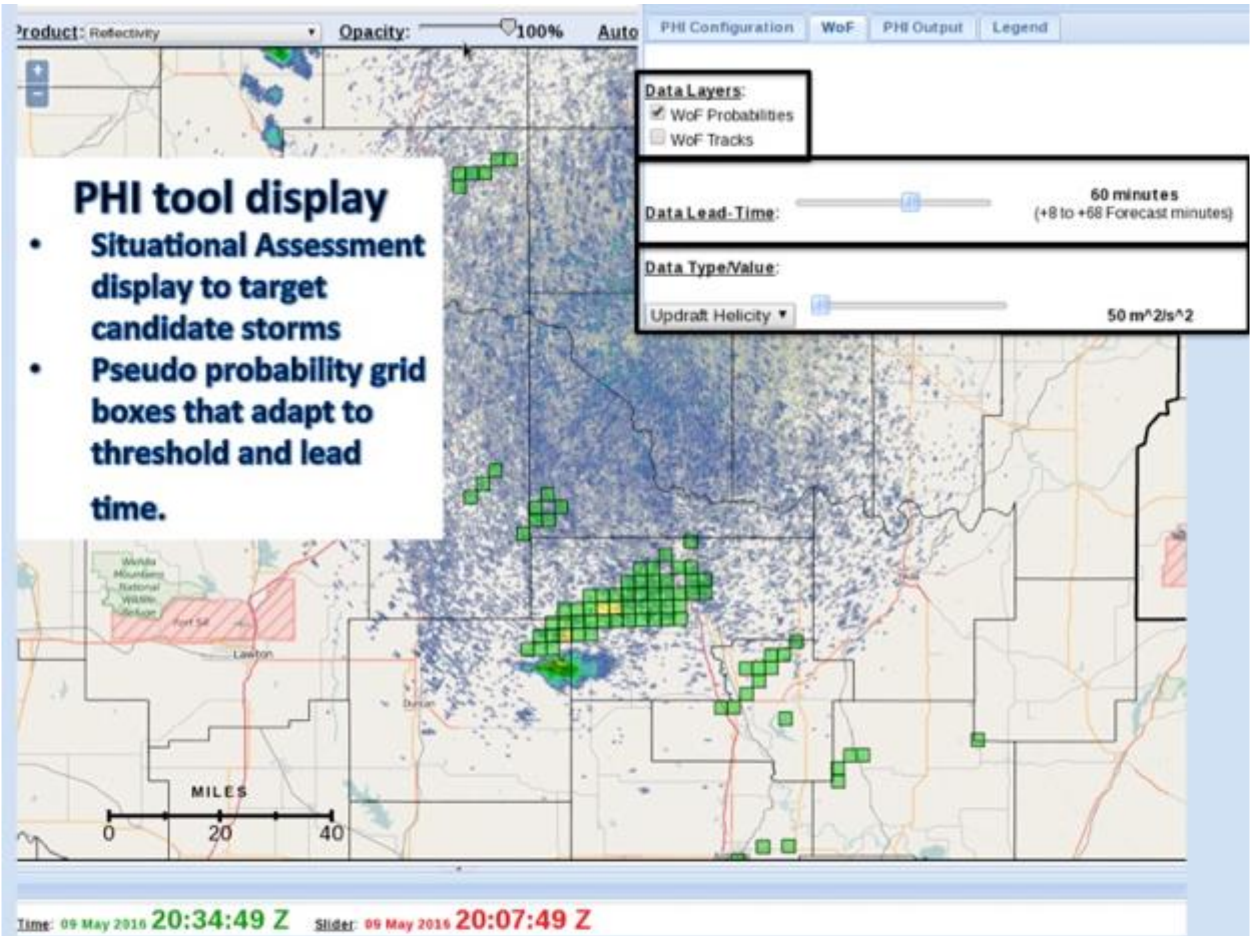
3. Tests and Evaluation of Rapid Post-Processing and Information Extraction from Large Convection-Allowing Ensembles Applied to 0-3hr Tornado Outlooks

James Correia Jr. (CIMMS and SPC)

The purpose of this project is to design, implement, and evaluate a new post-processing paradigm, designed for any convection-allowing modeling and ensemble system. This new paradigm will allow information extraction for severe weather forecasting, specifically tornado forecasts. This new post-processing paradigm has the benefit of being adaptable, scalable, and fast. To achieve these benefits, we propose using an object-based approach to refine gridded datasets into features of interest, a result of the data mining and information extraction, in order to achieve reduced dataset size for transmission, allow the viewing of all ensemble members, create an ability for forecasters to adapt to the problem of the day and maximize effective use of numerical guidance.

We utilized the NSSL Experimental Warn on forecast System for ensembles (NEWS-e) within the Hazardous Weather Testbed to generate tracks of rotating updrafts and low-level rotation for use during the Experimental Warning Program Probabilistic Hazard Information (PHI) experiment. In May – June 2016, nine forecasters were exposed to this information in an adaptable display designed to address the problem of the day, and allowed them to query the ensemble information contained within the tracks dataset to issue tornado PHI. The additional situational awareness provided what the forecasters called "hot spots" that they then could focus back on radar data to issue their warnings. Overall, the data and display were well received. The dataset itself was small, agile, and rapidly available.

This project is a necessary first step in achieving full use of rapidly updating, large convection-allowing ensemble systems and making them useful and usable to forecasters while producing consistent and reliable risk analyses in between the warning and watch time scales. This in turn, enables forecasters to provide effective decision support to help partners effectively mitigate the impacts of severe weather.



PHI tool display showing pseudo-probability grid (green & yellow squares) along with inset controls for querying the dataset. Queries were constrained to two variables (Updraft helicity for deep rotating updrafts and low-level vorticity for mesocyclones) and multiple magnitudes. Time was also an attribute that could be set for how far out in the forecast forecasters could see the 90-minute data. Using the queries, pseudo probabilities would be updated on the fly to see where storm features were moving, their intensity, and future location.

4. Computational Support for Warn on Forecast

Gerald Creager (CIMMS at NSSL) and Devin Smoot (NASA Space Grant and SWOSU)

Computational power remains the basis for and limitation of convection-allowing model systems. Warn-on-Forecast is no different. Over three years ago, NSSL acquired a Cray supercomputer, allowing several years of real-time experimentation during the spring convective season, as well as significant research into new processes and higher resolution operations. In addition, post processing has become a significant factor in completion of real-time model runs, since WoF has ramped to twice-hourly runs with full data assimilation. Creating several systems to offload real time processing has produced an ecosystem allowing generally unloaded analysis and graphical results

creation for a variety of users. Finally, storage space has long been a bottleneck for users. Originally, users would download runs to local desktop storage. This proved inefficient because of network performance limitations.

Over the course of the last year, projects have been undertaken to:

- Create and subsequently enhance a “second-tier” storage solution for the Cray, available beyond the Cray system to other intra-NSSL resources. This “slow” disk lacks the performance of the primary disk system on the Cray but allows relatively fast data transfer to a file system more readily available for either specialized (dedicated post-processing nodes) or general (desktop) analysis and review.
- Identify a requirement for post processing systems, and stand up prototypes, demonstrating the efficacy of their use. This experiment led to identifying, specifying and acquiring several dedicated systems for post processing with high CPU core counts, and significant investment in RAM (memory).
- Define requirements, gather information and quotes, and oversee acquisition of a new Cray supercomputer which is currently being installed at NSSL to replace the old system. In addition to the routine acquisition process, work was also undertaken to improve power distribution within the NSSL data center, which facilitated installation of the new Cray.

5. Management of Outreach Efforts

Gerald Creager (CIMMS at NSSL), Timothy Sliwinsky (Texas Tech University), and Marc Cotnoir (Consultant)

Several recurring outreach efforts involving CIMMS and NSSL are present. The annual High Performance Computing symposium at the American Meteorological Society Annual Meeting is one, where, unlike the normal AMS fare of meteorology, we explore the computational aspects, including computational science, software engineering and operational support, and their impacts on the work of operations and research in meteorology. Another topic is an annual, publicly advertised aviation weather symposium hosted at the National Weather Center. This effort, in concert with the Federal Aviation Administration's Safety Team, seeks to add to the knowledge of people in the aviation field, including pilots, by providing access to world-class scientists explaining pertinent topics in their fields. This year's AMS HPC symposium will represent the fourth annual conference. This year, Creager is chairing the conference, with assistance from Sliwinsky and Cotnoir.

The Aviation Weather symposium is taking on a higher profile this year due to becoming associated with a regional Fly-In sponsored by the Aircraft Owners and Pilots Association. Utilizing a group of experts from NOAA, CIMMS and OU-SOM, this symposium will provide information to a group of up to two hundred interested pilots and others. Topic range from observations and measurement systems, to creation of radar mosaics for use in the airplane, to the difficulties of all-seasons forecasting and specific

focus on winter weather forecasting. A demonstration and explanations of vertical profiles from balloon-borne radiosondes and unmanned aerial systems will also be given.

6. Citizen Weather Observing Program

Gerald Creager (CIMMS at NSSL)

Support the Citizen Weather Observing Program, a citizen-science-enabled project wherein volunteers provide automated surface observations to the Meteorological Assimilation Data Ingest System. CWOP represents the largest known mesonet in the world, with over 16.000 registered stations and almost 10,000 reporting on an hourly or more frequent basis. Creager has long acted as the manager for the distributed network of data servers, and has continued this effort. In addition, he has been involved in user support on an as-available basis. Server performance has approximated 100% availability of the entire network over the last year. Some of the user support has involved work directly with NWS WFOs, and personnel at NWS Headquarters to answer questions and help resolve issues with mistaken user ID entry.

7. Daily NSSL WRF, NMMB, and SREF-initialized Ensemble Members

Scott Dembek (CIMMS at NSSL), Adam Clark and Jack Kain (NSSL), and Israel Jirak (SPC)

Since the fall of 2006 Storm Prediction Center (SPC) forecasters have been using output from an experimental, modified version of the Weather Research and Forecasting (WRF) model in the production of their daily convective outlooks over the Continental United States (CONUS). The model, known as the NSSL WRF, runs twice daily at 0000 UTC and 1200 UTC on a full CONUS domain using a 4-km grid resolution, with forecasts out to 36 hours. The experimental forecast output provided by the NSSL WRF has proven to be a valuable tool for the SPC forecasters, owing to its convection-allowing dynamics and unique diagnostic fields that help identify the potential for convective-scale elements like supercells and bow echoes. This guidance is an aid in the determination of convective initiation, mode, intensity, areal coverage, and storm system evolution.

Another real-time NWP model running daily at NSSL is the NOAA Environmental Modeling System (NEMS) Nonhydrostatic Multi-scale Model on the B-grid (NMMB). The NSSL NMMB generates 36-hour forecast output once daily at 0000 UTC and covers the CONUS utilizing a latitude-longitude grid that approximates the grid used by the NSSL WRF. The NSSL NMMB has had unique diagnostics fields added to it, like those designed for the NSSL WRF. This allows the SPC forecasters to take advantage of a customized forecast product and make direct comparisons to the results generated by the NSSL WRF.

Also run daily at 0000 UTC is an ensemble of eight 4-km NSSL WRF forecasts utilizing the 3-hour output from NOAA's Short-Range Ensemble Forecast (SREF), initialized beginning at 2100 UTC the previous day. Each of these SREF-initialized NSSL WRF ensemble members uses the same physical parameterizations as the deterministic NSSL WRF, but allows the SPC forecasters to see the forecast spread associated with the various initial conditions used to generate the ensemble. The SREF members used to initialize the NSSL WRF ensemble include four Atmospheric Research WRF (ARW) members (arw_ctl, arw_p1, arw_n1, and arw_p2), and four NMMB members (nmmb_ctl, nmmb_p1, nmmb_n1, and nmmb_p2).

Production of the NSSL WRF, NSSL NMMB, and the eight-member NSSL WRF ensemble continues to be a valuable tool for SPC forecasters who find the unique products an asset as they generate their daily outlooks.

8. Support for the 2017 NOAA HWT Spring Forecast Experiment

Scott Dembek and Gerry Creager (CIMMS at NSSL), Adam Clark (NSSL), and Israel Jirak (SPC)

The annual Spring Forecast Experiment, a collaboration between the SPC and NSSL, is designed to improve the short-term forecasting of hazardous convective-weather events by testing the newest technologies used in experimental convection-allowing models (CAMs). Similar to previous SFEs, in 2017 a single framework was developed for coordinating contributions from various sources, creating an 81-member ensemble known as the Community Leveraged Unified Ensemble (CLUE).

Support for the 2017 Spring Forecast Experiment (SFE2017) included running the NSSL CLUE members, specifically a set of ensemble members testing forecast perturbations using single-physics with stochastic perturbations. The stochastic perturbations are created by applying Stochastic Parameter Perturbations (SPPs) in the MYNN PBL scheme and the RUC LSM. WRF code used to generate the stochastic perturbations was acquired from scientists at the NOAA Development Testbed Center, and ported to the Texas Advanced Computing Center at the University of Texas. Issues associated with the increased computational requirements of the stochastic-physics ensemble members prevented them from being run in real time, but the members are being run post-SFE2017. In additional, a set of NSSL NMMB single-physics ensemble members that were not able to run in real-time during SFE2017 will also be run post-experiment.

9. Technique to Assimilate Total Lightning Data in the Variational Framework at the Convection Allowing-to-Cloud Scales for High Impact Weather Events

Alexandre Fierro, Yunheng Wang, and Kristin Calhoun (CIMMS at NSSL), Jidong Gao, Don MacGorman, Ted Mansell, and Conrad Ziegler (NSSL), S Liu and Jacob Carley (NOAA NCEP), Y Li and K E Pickering (University of Maryland), Mark DeMaria (NOAA NHC), and Gang Zhao (CAPS)

Our goal was to develop and evaluate at least one technique to assimilate total lightning data in the variational framework at the convection allowing to the cloud scales for high impact weather events. Collaboration was made with NCEP partners (Geoffrey DiMego, Shun Liu, and Jacob Carley) to implement and test this new lightning data assimilation (LDA) technique within the GSI framework.

With the support of Gang Zhao (CAPS) and Yunheng Wang (NSSL), the LDA technique described above was successfully implemented in GSI v3.5 and in NSSL 3DVAR package called NEWS3DVAR on JET HPC Resources.

Both of these 3DVAR packages were tested in near real time over a dozen of high impact weather cases during the Spring of 2017 at convection-allowing scales (3-4 km) over CONUS and on the regional scale. These tests included several LDA set ups/experiments evaluating, for example, the impact of horizontal decorrelation scales and the strength of the DA. Traditional NCEP datasets (called PREPBUFR data) also were assimilated with and without lightning to consolidate the results/be more aligned with NCEP's methodology.

Following the guidance of NCEP (Sun Liu), the results of the forecasts described above were thoroughly analyzed following their metrics and methods. The results were briefed almost on a daily basis to NCEP collaborators.

Finally, collaboration was made with the University of Maryland to improve DC3 simulations using a lightning data assimilation developed in 2012 (Fierro et al. 2012). The results were recently published.

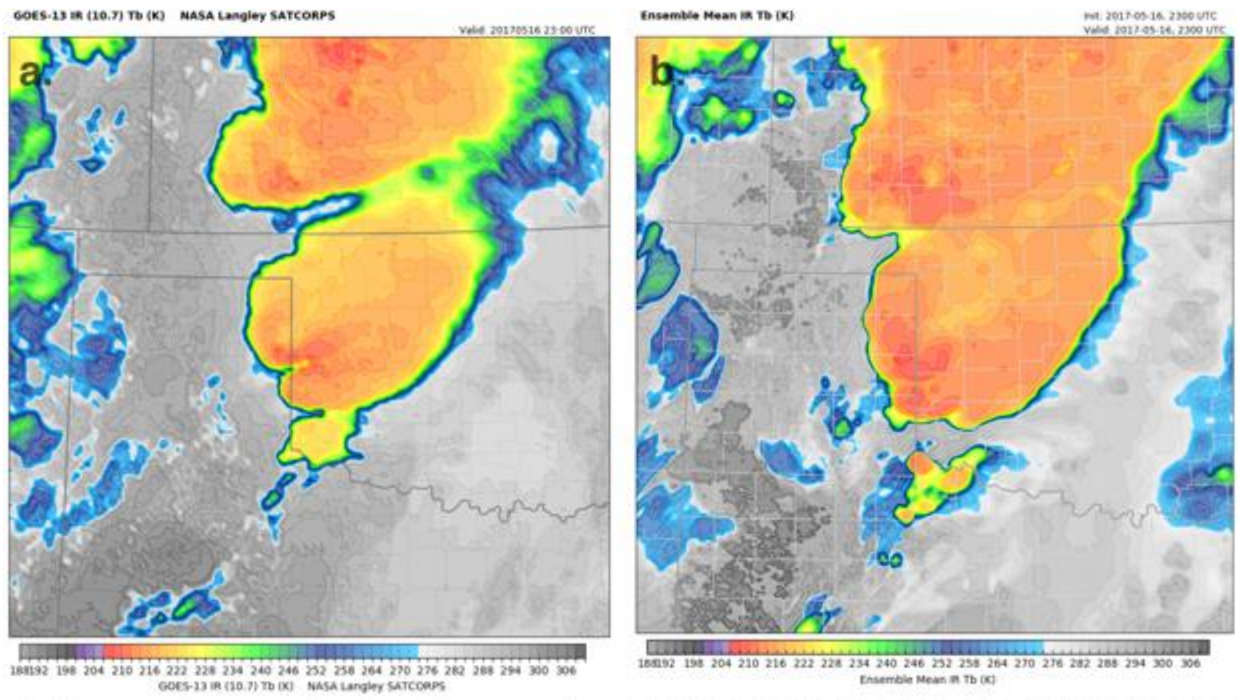
10. Storm-Scale Cloud Water Path Assimilation

Thomas Jones and Dustan Wheatley (CIMMS at NSSL), and Patrick Minnis (NASA Langley)

Research is ongoing towards assessing the impacts of assimilating GOES cloud water path (CWP) retrievals into convection permitting models. CWP was assimilated into the NSSL experimental WoF System for ensembles (NEWS-e) during realtime testing for the 2017 HWT experiment. Assimilating these observations generally resulted in improved thermodynamic conditions over the storm-scale domain through better analysis of cloud coverage compared to radar-only experiments. These improvements often corresponded to an improved analysis of supercell storms leading to better forecasts of reflectivity and updraft helicity. This positive impact was most evident for events where convection was not ongoing at the beginning of the radar and satellite data assimilation period.

During the 2017 HWT, simulated satellite imagery was generated for each forecast period and compared against observations. The figure below shows observed GOES-13 infrared channel (10.7 μm) brightness temperature along with the corresponding

ensemble mean simulated brightness temperature at 2300 UTC on 16 May 2017. The model analysis correctly analyzes the locations of deep convection its corresponding cirrus outflow as evidenced by the cold (< 220 K) brightness temperatures.



GOES-13 infrared brightness temperatures at 2300 UTC on 16 May 2016 (a) with corresponding ensemble mean simulated infrared brightness temperatures from the model analysis (b).

11. GOES Imager Water Vapor Channel Radiance Assimilation

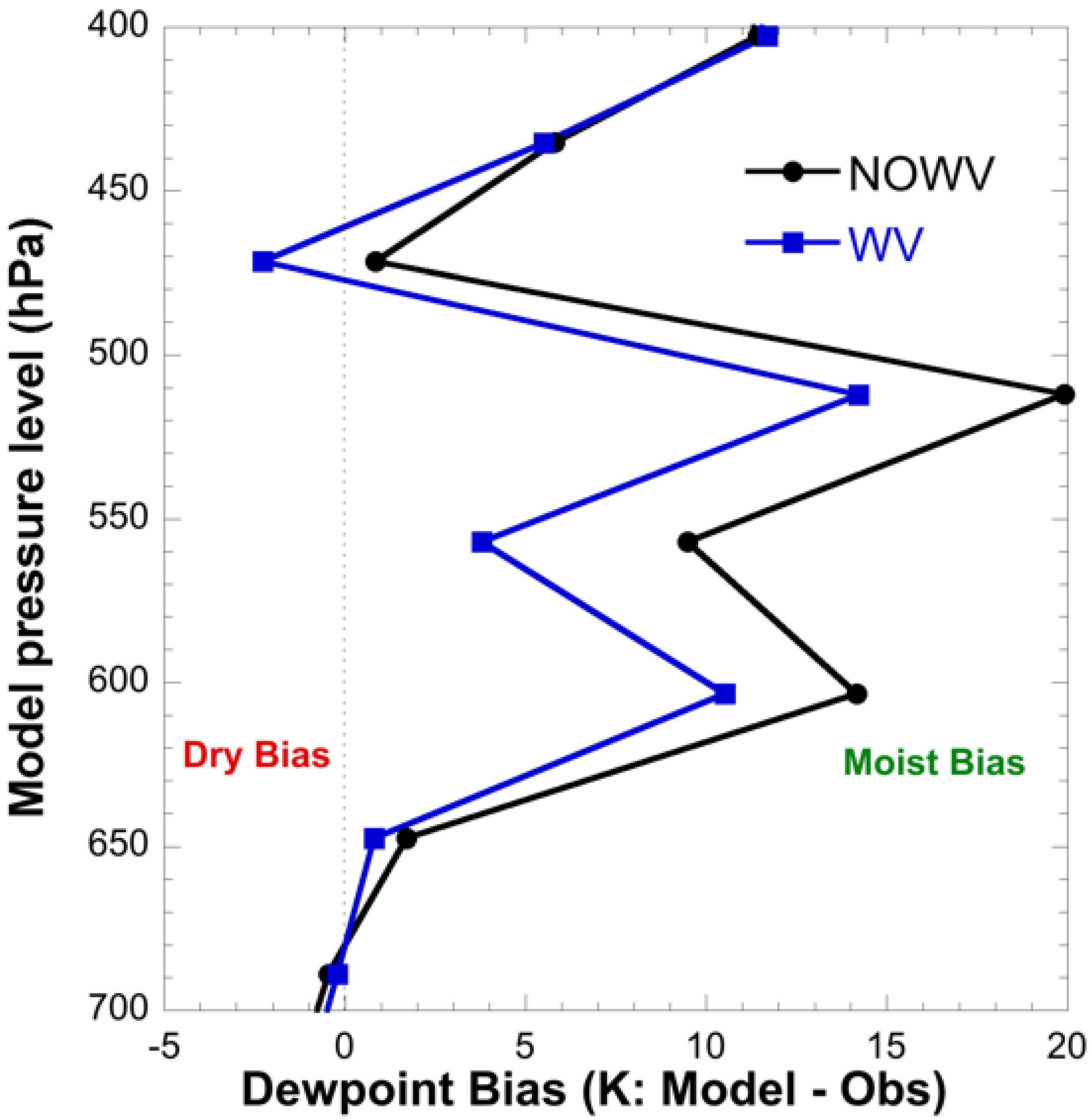
Thomas Jones (CIMMS at NSSL) and Jason Otkin (CIMSS-Wisconsin)

GOES-13 imager clear-sky water vapor radiances have been assimilated into several case study experiments that occurred during spring 2016. Initial results showed that assimilating these data had the desired impact on the mid-tropospheric moisture analysis, and lowered moisture errors when compared against experimental upper-air observations collected as part of the mini-Mesoscale Predictability Experiment (MPEX). These environmental changes also had an impact on the pre- and near-storm environment.

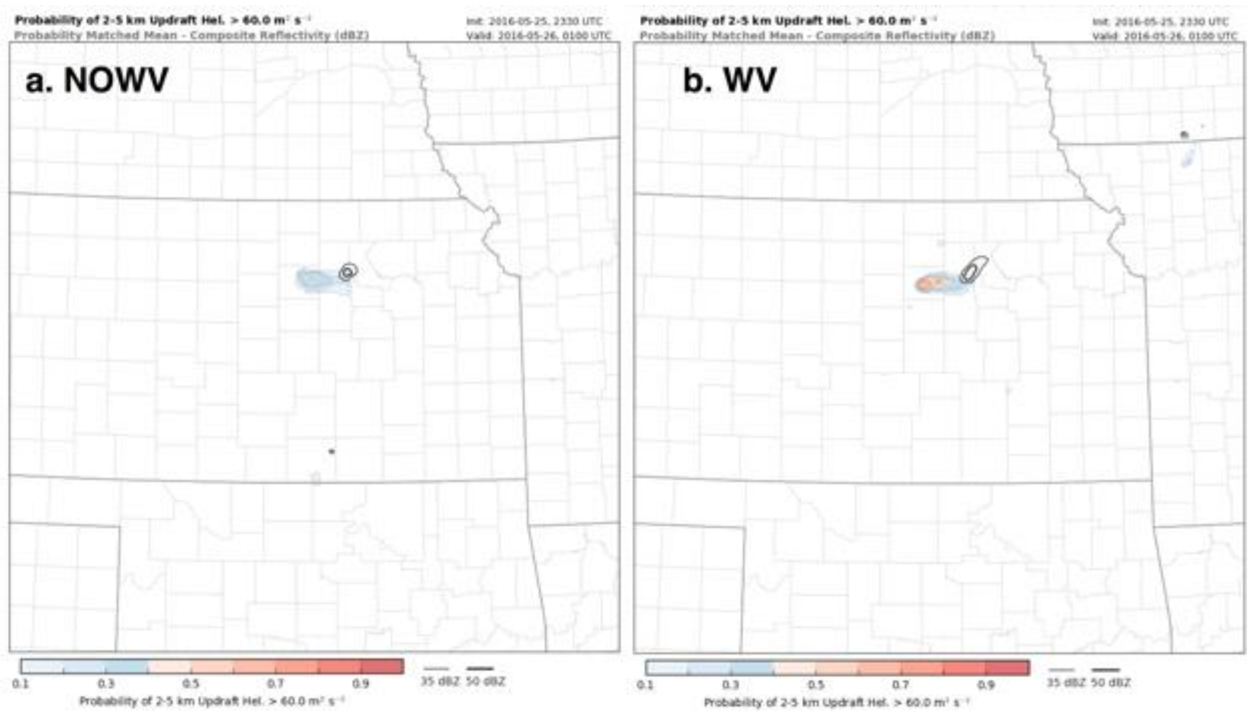
Two experiments were performed to determine the impact of assimilating water vapor radiances. The first, (NOWV), assimilates radar reflectivity, radial velocity, Oklahoma mesonet, and GOES-13 CWP retrievals. The second (WV) assimilates the same set of data, but with water vapor radiances now included. For an event occurring on 25 May 2016 in central Kansas, 90 minute forecasts beginning at 2330 UTC were generated from both experiments. The figure below shows the dew point bias (model-observation) for both NOWV and WV experiments between 800 – 300 hPa. The moist bias in the

model is clearly reduced in WV though it still exists to some degree. This may be due to the bias correction being somewhat too effective.

While assimilating water vapor radiances improved the environment, it important that this improvement translates into a better forecast of high impact weather. To evaluate this question, the probability of 2-5 km updraft helicity (UH) greater than 60 m^2 s^{-2} was generated from both sets of 90 minute forecasts. NOWV only generates probabilities < 40% indicating that a strong, rotating supercell is not generated by over half of the ensemble members (see figure below).



Ensemble mean dewpoint bias at ~2330 UTC for NOWV and WV (model – MPEX observation) between 700 – 400 hPa where the sensitivity of the water vapor is greatest. Positive values indicate a moist bias in the model while negative values indicate a dry bias in the model.



Probability of 2-5 km UH > 60 m^2 s^{-2} for NOWV (a) and WV (b) experiments for 90-minute forecasts initiated at 2330 UTC. Black contours represent probability matched mean forecast reflectivity at the end of the forecast period (0100 UTC).

12. Improving Storm-Scale QPF Forecasting through Assimilating New Datasets as part of the Joint Technology Transfer Initiative

Nusrat Yussouf and Thomas Jones (CIMMS at NSSL), and Jason Otkin and Tim Wagner (CIMSS-Wisconsin)

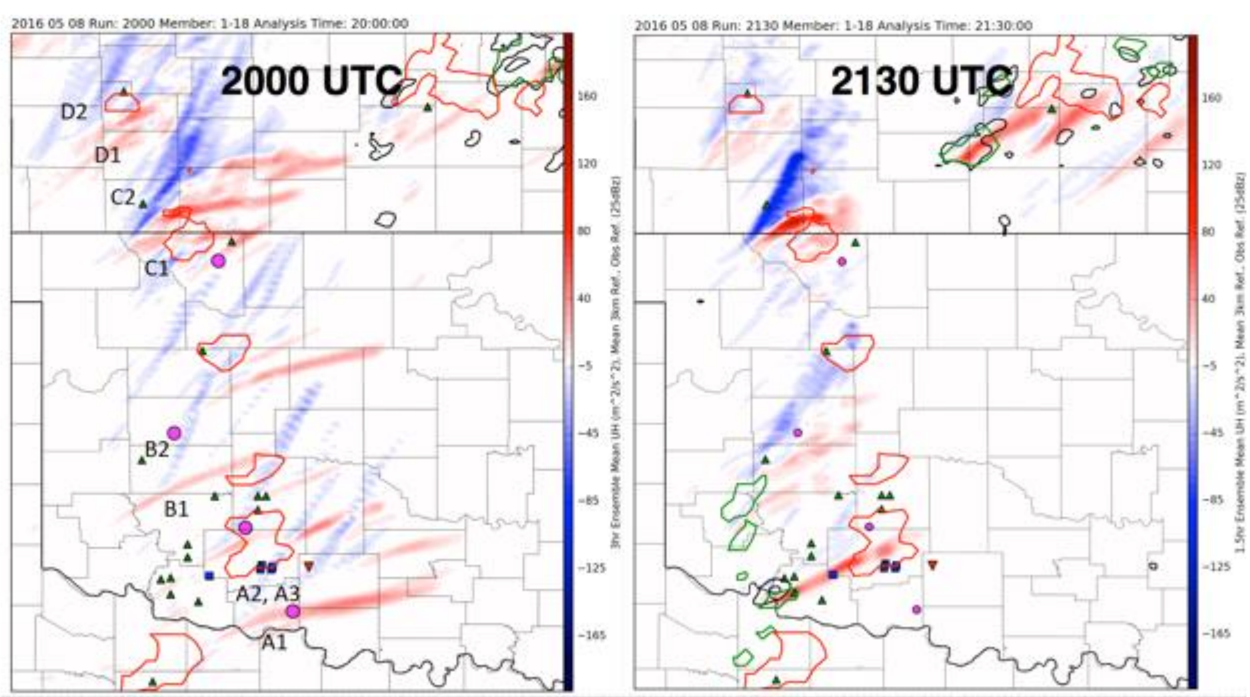
This research aims to improve 0-6 h convective-scale Quantitative Precipitation Forecasts (QPF and probabilistic QPF) and other high impact weather events. Recent study shows that advanced radar and satellite ensemble data assimilation techniques can provide skillful ~0-3 h intense convective rainfall forecasts in terms of location and amount. However, beyond 0-3 h time period, forecast errors grow more rapidly with sharp decrease in forecast skill, indicating that the impact of radar and satellite DA is greatest during early forecast hours. Better representation of the near storm environment in model initial condition is important to further improve forecast of precipitation and other hazardous convective events. The rapid temporal and spatial changes in the near storm environment are not well represented in the current convective-scale models due to the unavailability of high spatial and temporal resolution boundary layer observations. This work enhances the operational GSI-based EnKF data assimilation system using a convective-scale model (WRF-ARW) by including and refining the capability to assimilate ground based remote sensing boundary layer observations and GOES-16 water vapor satellite radiances to develop a frequent-update-cycle convective-scale ensemble data assimilation (DA) and prediction system. Satellite observations provide detailed properties of the mid- and upper-troposphere that

complement the boundary layer information provided by surface based profiling instruments.

13. Short-term Forecasts of Left-Moving Supercells from an Experimental Warn-on-Forecast System

Thomas Jones (CIMMS at NSSL) and Cameron Nixon (NOAA Hollings Scholar)

Hollings Scholar student Cameron Nixon analyzed the ability of the NEWS-e system to forecast left-split supercells in a mesoscale environment where both left and right splits were favorable. This environment was present over the Southern Plains during 8 May 2016 during which both left and right split supercells occurred. Both storm types produced numerous severe weather reports. Using “negative” updraft helicity, Cameron showed that the NEWS-e system can indeed forecast storm splitting and the persistence of left moving supercells in favorable environments. The figure below shows an example 3 hour forecast from 2000 UTC and 1.5 hour forecasts from 2130 UTC. Both positive (red) and negative (blue) ensemble mean updraft helicity forecasts are plotted and it is clearly evident that both left and right supercell tracks are forecast. This is an especially promising result since storm initiation had yet to occur in much of the model domain at 2000 UTC.



Mean updraft helicity for 0-3 hour forecasts beginning at 2000 UTC (left) and 1.5 hour forecasts beginning at 2130 UTC (right). Positive values (red) indicate cyclonic rotation while negative values (blue) indicate anti-cyclonic rotation. Red contours indicate location of observed reflectivity at 2300 UTC.

14. Impact of the Assimilation of Hyperspectral Infrared Radiances into the High-resolution WoF GSI-EnKF System

Thomas Jones and Swapan Mallick (CIMMS at NSSL)

The accuracy of numerical weather prediction (NWP) largely depends on the initial conditions of the atmospheric state. Assimilation of satellite infrared radiances into convection allowing (~3 km) NWP models have the potential to improve the model analysis where conventional observations are sparse. However, many challenges remain on how best to accomplish this task. The proposed work aims to improve short-term (0-3 hour) forecasts of high impact weather by assimilating the clear-sky satellite hyperspectral radiances. One dataset is from Atmospheric Infrared Sounder (AIRS) instruments on board the Earth Observing System (EOS) Aqua satellite. The other dataset is from the Cross-track Infrared Sounder (CrIS) on board the Suomi-NPP (National Polar-orbiting Partnership) spacecraft. These datasets are assimilated into the Gridpoint Statistical Interpolation (GSI) based Ensemble Kalman Filter (EnKF) assimilation system connected to the WRF-ARW model core which is one of several potential configurations being tested for an operational Warn-on-Forecast (WoF) system. Several convective events were considered in this study during the year 2016 to assess the potential of assimilating satellite hyperspectral radiances into a WoF system to improving forecasts of high impact weather events.

15. Storm-scale Data Assimilation and Ensemble Forecasting for Warn-on-Forecast

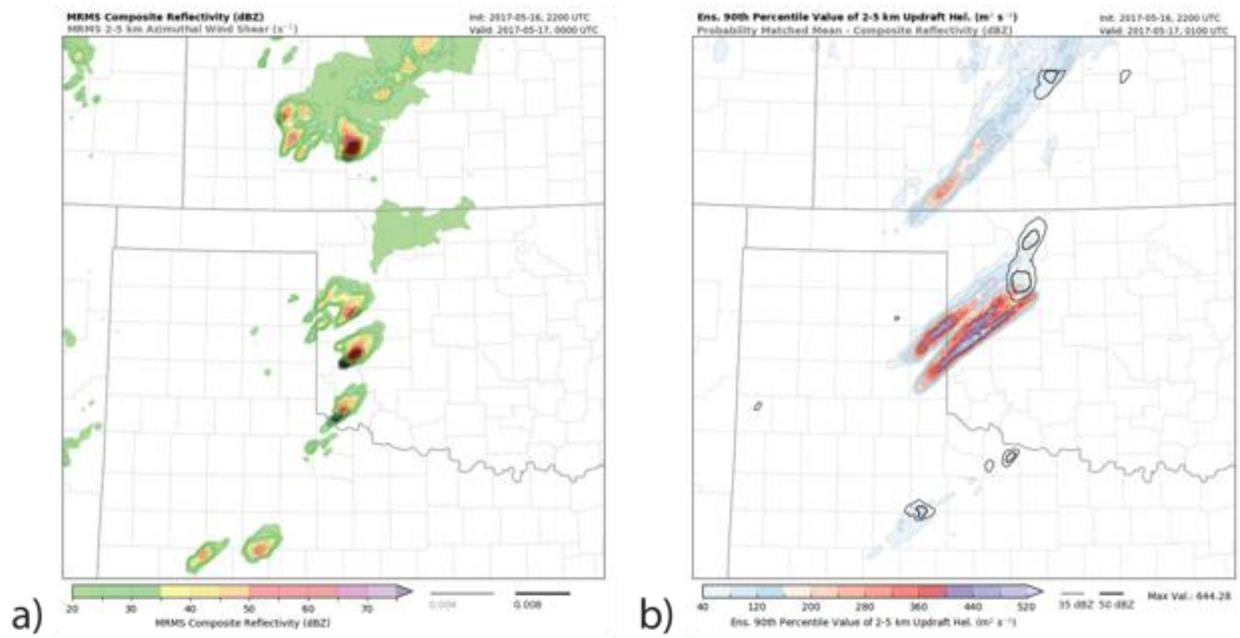
Kent Knopfmeier, Dustan Wheatley, Thomas Jones, Patrick Skinner, Jessica Choate, and Gerry Creager (CIMMS at NSSL)

During spring 2017, the NEWS-e was run in realtime each day from 1 May – 9 June, which coincided with the 2017 NOAA HWT-SFE. The 3-km, hourly cycled HRRR Ensemble (HRRRE), currently under development at ESRL/GSD, provided both the initial and boundary conditions for the NEWS-e, a 36-member, 3-km, WRF-based ensemble. The NEWS-e domain, which covered a 750-km wide region encompassing the area where severe weather was expected to occur, was chosen daily through coordination with SPC forecasters and participants in the 2017 HWT-SFE. METAR, Oklahoma Mesonet (when available), MRMS radar reflectivity, WSR-88D radial velocity, and satellite (cloud/ice water path retrievals) data were assimilated every 15-min using the ensemble adjustment Kalman filter (EAKF) code present in the Data Assimilation Research Testbed (DART) software. 18-member forecasts were generated from the NEWS-e analyses every half hour, including a 4-hour forecast at 1900 UTC, a 3-hour forecast at the top of each hour from 2000 – 0300 UTC, and a 90-min forecast at the bottom of the hour over the same period. To facilitate communication of the NEWS-e forecasts, a web-based forecast viewer (http://www.nssl.noaa.gov/projects/wof/news-e/images.php) was developed. Numerous output fields were generated, such as basic environmental information (i.e. temperature), rainfall, simulated reflectivity, low-level rotation (i.e. 0-2 km updraft helicity and vorticity), and mid-level rotation (i.e. 2-5 km updraft helicity). The focus of this year's experiment with the NEWS-e was providing

data for both experimental and operational activities being conducted at the National Weather Center.

The experimental forecast activity was completed during the HWT-SFE, and consisted of issuing two severe weather outlooks valid between 2100 – 2200 UTC and 2200 – 2300 UTC. These outlooks were similar to the daily SPC daily convective outlooks, but on a much higher temporal scale. The 4-h NEWS-e forecast valid from 1900 – 2300 UTC was used to generate the first set of outlooks by 2030 UTC. Then, the outlooks were updated by 2100 UTC using new guidance provided by the 2000 UTC NEWS-e forecast. On the following day, these outlooks were subjectively verified by HWT-SFE participants using observed storm reports and NWS warning polygons.

The NEWS-e forecasts were used operationally by forecasters at the Norman, OK NWSFO (Norman FO) on days when the NEWS-e domain included their forecast area. The forecasts proved useful, especially on 16 May 2017, when an EF-2 tornado struck the town of Elk City in western Oklahoma. The Norman FO utilized NEWS-e forecast information up to three hours prior to tornado formation to issue an advisory for four southwestern Oklahoma counties alerting emergency managers and citizens that tornado warnings would likely be issued. The high probabilities of rotation indicated by subsequent NEWS-e forecasts gave the Norman FO forecasters high confidence that strongly rotating supercell thunderstorms would affect the advisory area. It enabled tornado warnings to be issued with greater lead time and allowed emergency managers to activate outdoor warning sirens ~ 30 min ahead of the tornado. For more information, please see the NOAA press release (http://www.noaa.gov/stories/experimental-model-predicted-tornados-path-hours-not-minutes-before-it-formed).



a) MRMS composite reflectivity (dBZ; see label bar) and MRMS 2-5 km azimuthal wind shear (s^{-1}; see legend) valid at 0000 UTC 17 May 2017. b) Ensemble 90th percentile value of 2-5 km updraft helicity (m^2 s^{-2}; see label bar) at each model gridpoint over the 3-hr forecast period 2200 UTC 16 May 2017 – 0100 UTC 17 May 2017 and the probability matched mean composite reflectivity (black contours; see legend) at 0100 UTC 17 May 2017.

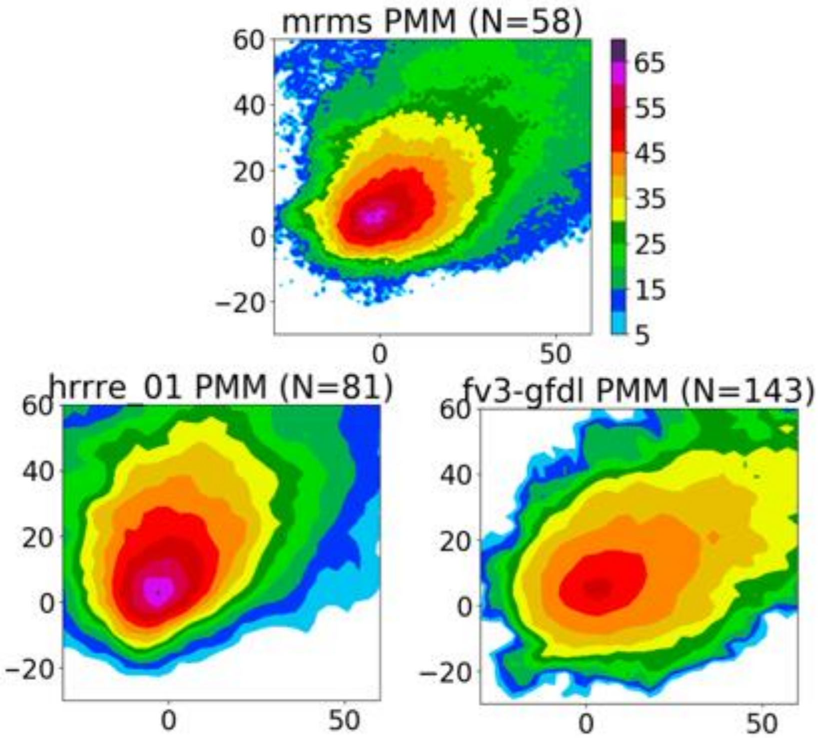
16. Inter-Model Comparisons of Storm-Scale Forecasts from the HWT Spring Forecasting Experiment

Corey Potvin, Anthony Reinhart, and Patrick Skinner (CIMMS at NSSL), Adam Clark, Lou Wicker, and Jack Kain (NSSL), and Jacob Carley (NOAA NCEP)

The 2016 and 2017 NOAA Hazardous Weather Testbed (HWT) Spring Forecasting Experiments (SFE) have featured the Community Leveraged Unified Ensemble (CLUE), a coordinated convection-allowing model (CAM) ensemble framework designed to provide empirical guidance for optimizing CAM ensemble design. The 2017 CLUE included 81 members that all used 3-km horizontal grid spacing, allowing direct comparison of forecasts generated using different dynamical cores, physics schemes, and initialization procedures. The 3-km grid spacing also facilitates comparison to operational CAMs such as the NAM CONUS nest.

The 2017 CLUE output is leveraged to evaluate and compare the capability of various experimental and operational CAMs to realistically represent thunderstorms. A major focus is identifying relative strengths and weaknesses of the ARW, NMM-B, and FV3 dynamical cores. The assessment is concerned not so much with the accuracy of forecast timing and locations of individual storms, but with the general realism of storms

simulated by each model. The focus is therefore on generating and comparing climatologies from the CLUE models and corresponding NSSL MRMS products. A feature-based approach is used to focus the analysis on critical thunderstorm properties such as size, motion, updraft helicity, rainfall, and diurnal cycle. Preliminary results from a wide range of metrics reveal operationally important model differences that correlate with dynamical core. The outcomes of this and other inter-CAM evaluation studies will be crucial for the development and optimization of future, operational CAM systems and associated ensembles. Experimental work comparing WRF-ARW and NMM-B capabilities for simulating and predicting convection began during the period with funding awarded through the CIMMS Director's Discretionary Research Fund.



Probability-matched medians of supercell composite reflectivity for (top) MRMS, (left) HRRRE and (right) FV3-GFDL from 2017 HWT CLUE.

17. Investigating Supercell Sensitivity to Initial Condition

Montgomery Flora and Corey Potvin (CIMMS at NSSL), and Lou Wicker (NSSL)

As convection-allowing ensembles are now routinely used to explicitly forecast the evolution of severe thunderstorms, developing an understanding of the limits of storm-scale predictability is warranted. The motivation for this study largely stems from the NOAA Warn-on-Forecast (WoF) program and the need for a suitable full-physics/real-data numerical weather prediction (NWP) framework for studying storm-scale predictability. Using the aforementioned framework, the sensitivity of ensemble forecasts of supercells to initial condition (IC) uncertainty is investigated. Three sets of

ICs for our simulations were generated from the real-time NSSL Experimental WoF System for Ensembles (NEWS-e) during the 2016 NOAA Hazardous Weather Testbed Spring Forecasting Experiment. Simulations were initialized with developing thunderstorms and integrated for 3 h. The forecast sensitivity to IC uncertainty was assessed by repeating the simulations with the initial ensemble perturbations reduced to 50 %, 25 %, and 10% of their original magnitudes. Supercell features examined include mid- and low-level mesocyclone, updraft, downdraft, severe surface winds, and rainfall.

Forecast spread was substantially reduced with decreasing IC spread for all examined supercell features in all three cases. In cases where storm lifetime is only 3 - 4 h an intrinsic predictability limit (IPL; i.e., the lead time beyond which forecast uncertainty can no longer be reduced by decreasing IC uncertainty) may not exist. Upon reaching the IPL, the forecast spread can remain modest, allowing the practical predictability limit (i.e., the lead time beyond which the forecast becomes too uncertain to be useful) to exceed the IPL. Comparing to previous work, initializing post-convective initiation (CI) rather than pre-CI substantially improves predictability. Similar to tropical cyclones, storm location was far more predictable than a given feature's intensity.

Impacts of IC uncertainty within vs. outside of the storm were also explored. Forecast spread for all supercell features in all three cases benefited greatly early on from reducing intra-storm ensemble perturbations to zero (e.g., storm certainty). Forecasts benefited more from eliminating uncertainty in the storm environment (e.g., environment certainty) later in the simulations, but the results were more case-dependent. Storm certainty reduced forecast location spread for lead times of up to 2-3 h. Low-level rotation was more sensitive to intra-storm perturbations than environment perturbations, suggesting that tornado forecasts out to lead times of 1.5 – 2 h would benefit more from improving initial storm state certainty.

18. Correcting Phase Errors in EnKF Data Assimilation

Derek Stratman (NSSL/NRC Post Doc), Corey Potvin (CIMMS at NSSL), and Lou Wicker (NSSL)

A goal of Warn-on-Forecast (WoF) is to develop forecasting systems that produce accurate analyses and forecasts of severe weather, such as supercells, for forecasters to utilize in operational warning settings. Recent WoF-related studies have indicated the need to alleviate storm displacement errors in both storm-scale analyses and short-term forecasts. One promising method to reduce these errors is the feature alignment technique (FAT). The FAT mitigates displacement errors between observations and a model field while adhering to constraints to form a 2-D field of displacement vectors, which are used to adjust the prior model fields to more closely match the observations. Previous studies merging FAT with variational data assimilation systems have shown substantial improvement of analyses and forecasts, especially at earlier forecast times, by minimizing displacement errors. However, the WoF project mostly employs variants of the ensemble Kalman filter (EnKF) data assimilation technique to produce analyses. Therefore, this project merges the FAT with the CM1-LETKF (local ensemble transform

Kalman filter) system to vet the FAT as a potential alleviator of errors associated with storm displacement errors using observation system simulation experiments (OSSEs).

An idealized nature run of a supercell on a 250-m grid is used to generate pseudo-radar observations (i.e., reflectivity and radial velocity). Analyses and forecasts of a supercell are produced on a 2-km grid using 50-member ensembles to test the capabilities and sensitivities of the FAT. The FAT uses the composite reflectivity field to generate a 2-D field of displacement vectors and applies the vectors to the model state variables at the start of each LETKF analysis cycle. The FAT-LETKF system is tested by displacing initial background fields and modifying the environmental vertical profile to produce various sources of error without substantially changing the structure of the storm. The results from these tests reveal the beneficial impact the FAT-LETKF system may have in cases of storm motion bias resulting from mesoscale analysis or model errors. The supercell OSSEs provide the foundation for future FAT-EnKF experiments with real data.

19. Identifying and Correcting Reporting Biases in SPC Tornado Database

Corey Potvin and Patrick Skinner (CIMMS at NSSL), Chris Broyles (SPC), and Harold Brooks (NSSL)

Maximizing the value of tornado climatologies requires accounting for unreported or mischaracterized tornadoes, especially where people and damage indicators are sparse. Previous attempts to spatially model tornado reporting bias have used only a single variable (e.g., population density) or a combination of variables that are implicitly assumed to have mutually independent effects. The proposed methodology, on the other hand, uses multivariable polynomial regression to simultaneously account for several variables, along with potentially important variable interactions (e.g., reduced importance of population density to reporting bias for tornadoes occurring near major highways). Reporting bias is estimated at each grid point by treating tornado counts valid over 100K cities (i.e., population > 100,000) or NWS Weather Forecast Offices (WFOs) as unbiased estimates of the true tornado counts. The regression model is then applied to these noisy (due to sampling error) estimates to produce new reporting bias estimates that eliminate most of the noise while preserving important spatial relationships with the geopolitical variables. While the approach is developed using the U.S. Storm Prediction Center (SPC) tornado database, it can be valuably applied to anywhere tornado locations are recorded and GIS data on population, cities, and/or roads are available.

Tornado reporting bias is modeled east of the Rocky Mountains during 1975-2014 with various combinations of the following variables: 1) population density; 2) terrain ruggedness; 3) road density; and distance to 4) nearest 100K city, 5) 5K city, 6) WFO, 7) interstate, 8) WFO *or* 100K city, and 9) interstate *or* 5K city. In cross-validation tests, the combination of variables 1, 2, 4, 6, and 9 accounts for the most variance in reporting bias. Estimates of large-scale [*O*(1000 km)] reporting bias are not unduly sensitive to the number of regression variables, indicating useful information can be gained from

limited geopolitical data. However, cross-validation tests and geographic maps of modeled bias suggest more complex regressions substantially improve bias estimates at smaller scales. The resulting improvements to tornado hazard models would be valuable to forecasters, severe storm and climate scientists, and insurance/reinsurance companies.

The regressions suggest only 46 % of tornadoes that actually occurred in the analysis domain were reported, with reporting rate decreasing by half as distance to nearest 100K+ city increases to 50 km. Reporting biases are especially pronounced earlier in the record and for shorter-track tornadoes, but remain nontrivial even for more recent and longer-track tornadoes. Underestimation of tornado frequency *increases* with damage rating; for example, the actual frequency of EF/F 3-5 tornadoes appears to be nearly three times that in the record. This underscores the problem of under-rating tornadoes in rural areas.

20. Advanced Dual-Doppler Wind Retrieval Techniques

Nathan Dahl and Alan Shapiro (OU School of Meteorology), Corey Potvin (CIMMS at NSSL), and Adam Theisen (CIMMS at OU)

Observing System Simulation Experiments (OSSEs) are being conducted to finalize radar scanning strategies for IOPs to be conducted at the ARM SGP site. The collected X-band radar and vertical wind profiler datasets will be used to test novel, sophisticated techniques for improving dual-Doppler wind retrieval, and to compare wind analyses obtained from dual-Doppler retrieval and ensemble data assimilation.

21. Evaluating Radar-derived Low-level Circulation and Expansion Rate as Predictors for Supercell Tornadogenesis

Vincent Wood (NSSL), Corey Potvin (CIMMS at NSSL), and Robert Davies-Jones (NSSL Emeritus)

Circulation and areal expansion rate may be more useful than differential single-Doppler velocities in the characteristic velocity couplet for detecting and measuring the strength of convergent tornadic mesocyclones at low altitudes, because circulation and areal expansion rate are (a) less scale dependent, (b) more tolerant of noisy Doppler velocity data, and (c) relatively insensitive to range and azimuth, beamwidth and location of a tornado within a sampling volume. These metrics may therefore enable improved tornado detection and prediction algorithms.

An idealized, 111-m WRF-ARW simulation of a tornadic supercell is used to generated virtual Doppler radar data. Estimates of low-level supercell circulation and areal contraction rate are then diagnosed from the virtual radar data. Trends in these metrics leading up to tornadogenesis support their hypothesized value to tornado warning operations.

22. Visualization of High-Resolution Supercell Simulations

Greg Foss (Texas Advanced Computing Center), Amy McGovern (OU Department of Computer Science), and Corey Potvin (CIMMS at NSSL)

Scientific advice is being provided for a supercell visualization project at the Texas Advanced Computing Center. This project is intended to assist McGovern and Potvin's project to use advanced spatiotemporal data mining to identify precursors of tornadoes in supercell thunderstorm simulations. High-quality 3-D movies are being developed to help develop the object definitions for the data mining, to ensure automatically extracted objects match subjectively (visually) identified objects, and to develop definitions for new objects.

23. SPC HREF Ensemble Viewer

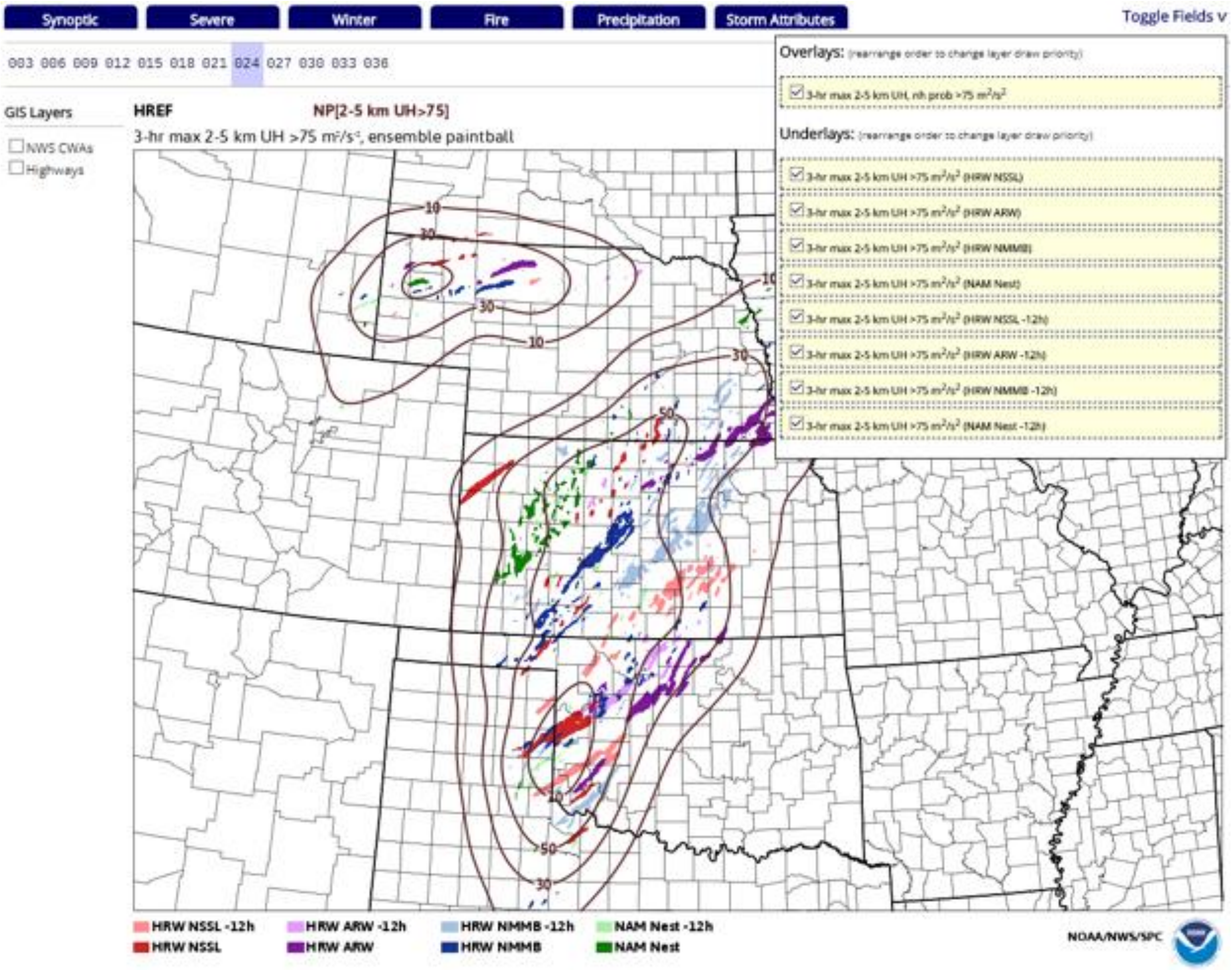
Brett Roberts (CIMMS at NSSL), Israel Jirak (SPC), and Adam Clark (NSSL)

As part of the Hazardous Weather Testbed's Spring Experiment, the Experimental Forecast Program (EFP) operates each year during May and June. A major focus of the EFP is the evaluation of emerging convection-allowing models (CAMs) in the context of forecasting severe convective storms. For the past several years, objective and subjective evaluations of CAMs in the EFP have indicated that the Storm-Scale Ensemble of Opportunity (SSEO) is the best-performing CAM ensemble among those evaluated. The success of the SSEO, an informal ensemble pioneered and processed at SPC, guided the development of the next-generation High Resolution Ensemble Forecast (HREF) system, an eight-member CAM ensemble with 3-km grid spacing. The HREF is scheduled to be implemented operationally at NCEP in late 2017, and will effectively replace the SSEO.

In preparation for the formal operationalization of the HREF, a website is under development to make operationally-relevant ensemble products easily accessible to NWS/SPC and other forecasters. This website features numerous products utilizing hourly-maximum fields (HMFs) such as updraft helicity, updraft speed, simulated reflectivity, and wind gusts. Ensemble neighborhood probabilities of exceeding a threshold are calculated for these HMFs, in addition to ensemble mean, minimum/maximum, and probability-matched mean fields. Other ensemble display techniques, such as pane-per-member "postage stamp" plots and "paintball plots" for member threshold exceedance, are also employed. Verification statistics and overlays for old model runs are also planned. This website represents the first such display of its kind for an operational CAM ensemble and a new tool to aid SPC forecasters in evaluating the risk of severe weather hazards.

After internal evaluation, the HREF Ensemble Viewer will be made available on the public SPC website this fall. The backend and framework developed for this website will also serve as the basis for an HWT CAM Viewer planned for implementation in the 2018

EFP, which will support ongoing research-to-operations work evaluating experimental CAMs and CAM ensembles.



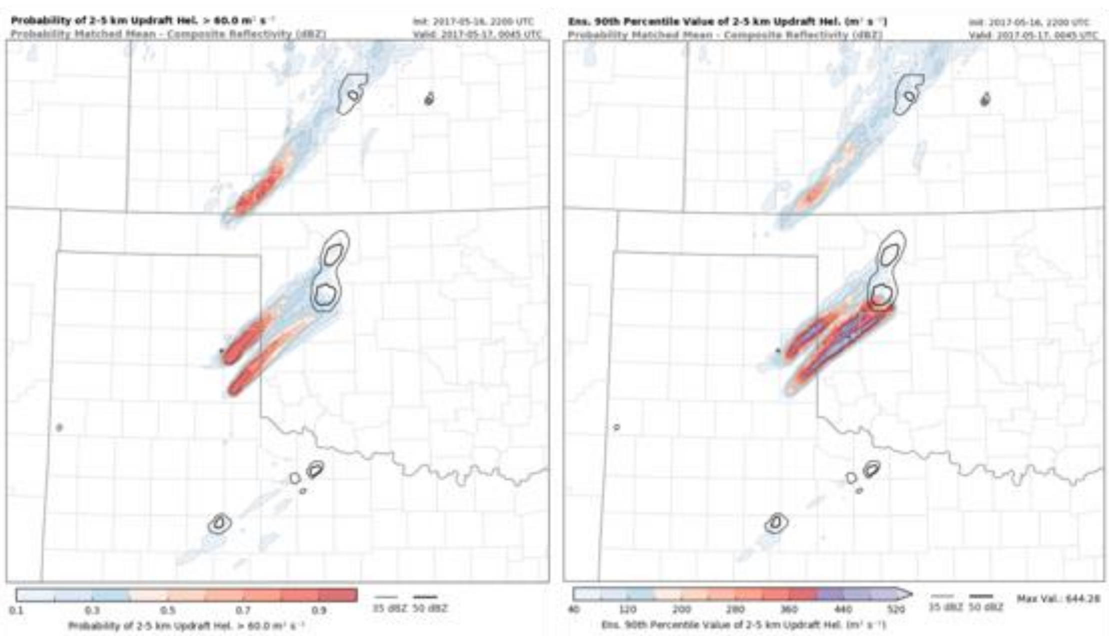
Preliminary version of the SPC HREF Ensemble Viewer website displaying a 24-hour forecast from the HREF run initialized at 00 UTC on 16 May 2017. "Paintballs" are displayed where 2-5 km AGL updraft helicity exceeds 75 m^2/s^2 for each member over the 3-hr period preceding 00 UTC on 17 May 2017. Contours for the smoothed ensemble neighborhood probability (r = 40 km) of updraft helicity exceeding 75 m^2/s^2 for the same period are overlaid. Each member's paintball plot, as well as the neighborhood probability contours, can be toggled as desired by the forecaster. Around the end of this 3-hour period, a damaging tornado struck Elk City, OK, located near the center of the region enclosed by the 70% probability contour.

24. Visualization and Verification of a Prototype Warn-on-Forecast System

Patrick Skinner, Dustan Wheatley, Kent Knopfmeier, Anthony Reinhart, Jessica Choate, Thomas Jones, and Gerry Creager (CIMMS at NSSL), and David Dowell, Therese Ladwig, and Curtis Alexander (NOA ESRL/GSD)

The NSSL Experimental Warn-on-Forecast System for ensembles (NEWS-e) has been used to produce short-term (0-3 hour) forecasts of thunderstorm hazards in real time during the springs of 2015–2017. NEWS-e produces 18-member forecasts with output available every 5 minutes twice hourly, resulting in an exorbitant amount of data to post-process and provide for forecasters. Work on post-processing of NEWS-e data has focused on two areas: Visualization of ensemble products that can be provided to forecasters with minimal latency and development of verification techniques for thunderstorm hazard forecasts to establish a baseline of system performance.

Over 100 ensemble products from NEWS-e forecasts were generated and provided to forecasters in the Hazardous Weather Testbed and Norman Weather Forecast Office within 30 (45) minutes of forecast initialization for 90 (180) minute forecasts. Additionally, real-time, object-based verification of NEWS-e forecasts was provided using Multi-Radar Multi-Sensor data as a verification dataset for thunderstorm hazards. Over 1,000,000 (500,000) reflectivity (updraft helicity) objects have been identified in NEWS-e forecasts from 2016 and 2017. This database is being used to establish a baseline of NEWS-e forecast performance for thunderstorm forecasts and guide changes in system configuration for future experiments.



NEWS-e 165-minute forecast swaths of (left) probability of 2-5 km updraft helicity exceeding 40 m^2 s^{-2} and (right) ensemble 90th percentile value of 2-5 km updraft helicity for a forecast issued at 2200 UTC 16 May 2017. The probability and percentile products provide measures of the likelihood and maximum severity of mesocyclones occurring during the forecast period, respectively.

25. Performance of a Prototype Warn-on-Forecast System during VORTEX-SE

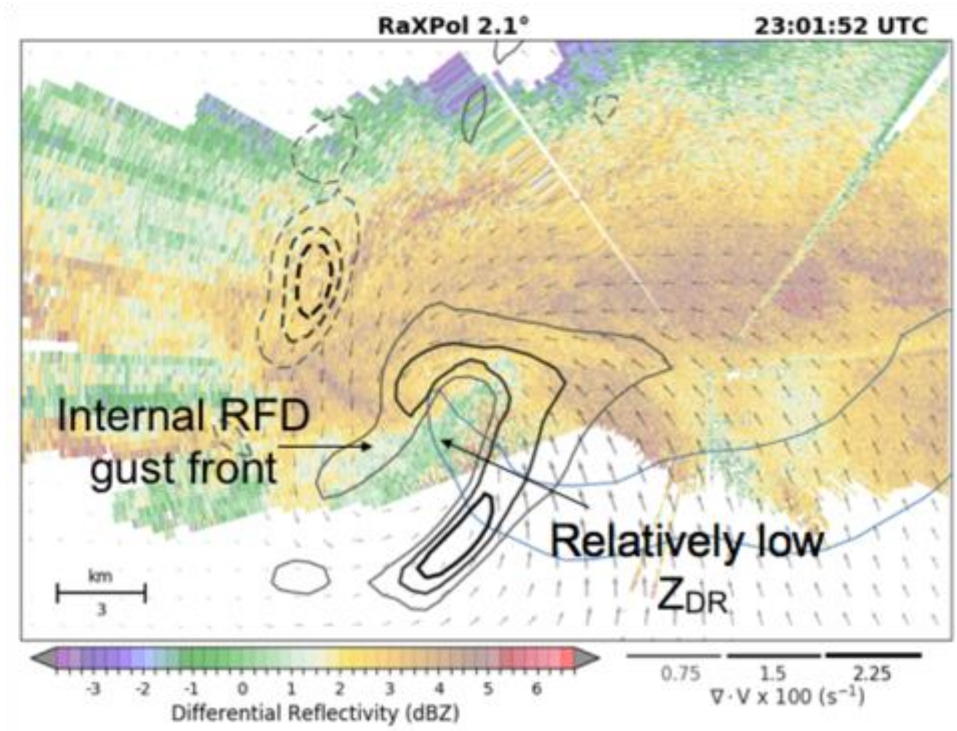
Patrick Skinner, Dustan Wheatley, Kent Knopfmeier, and Corey Potvin (CIMMS at NSSL), and Lou Wicker (NSSL)

A subset of 8 NSSL Experimental Warn-on-Forecast System for ensembles (NEWS-e) cases have been developed to examine system performance for cool season thunderstorm prediction in the southeastern United States. Object-based and subjective verification of thunderstorm hazards for these forecasts have been compared to NEWS-e forecasts for spring thunderstorms in the Great Plains. It has been found that NEWS-e typically performs worse for low-CAPE, high shear cases in the southeastern United States. Specifically, small errors in initiating boundaries and small storm size with rapid evolution have been identified as having a detrimental impact on NEWS-e forecasts.

26. EnKF and Polarimetric Analyses of the 31 May 2013 El Reno, Oklahoma Supercell during Tornado Genesis

Patrick Skinner and Jeff Snyder (CIMMS at NSSL), Lou Wicker (NSSL), Howard Bluestein (OU School of Meteorology), and Kyle Thiem (NWSFO Atlanta)

Specialized Doppler radar datasets collected by the RaXPol and Multifunction Phased Array Radar during the 31 May 2013 El Reno, Oklahoma tornado have been assimilated into an ensemble of numerical models using an Ensemble Kalman Filter (EnKF) technique. The resulting ensemble mean analyses are available with 500 m horizontal grid spacing for each minute for a 26-minute period centered on tornado genesis. The retrieved three-dimensional wind field of the supercell is compared with high-resolution RaXPol polarimetric data to identify the physical mechanisms producing polarimetric signatures. For example, a dramatic reduction of differential reflectivity (Z_{DR}) occurs in the broad rear-flank downdraft (RFD) south of the low-level mesocyclone during the 4 minutes preceding tornado genesis. This reduction occurs coincident with the development of an internal RFD momentum surge and the gust front on the leading edge of the surge demarcates the lower Z_{DR} values in the broad RFD from higher values within the surge. It is hypothesized that the reduced Z_{DR} values south of the low-level mesocyclone, which have been observed in several other tornadic supercells, may indicate an RFD surge is occurring that can contribute to tornado genesis.



RaXPol 2.1 degree elevation differential reflectivity (Z_{DR}; dBZ) at roughly the time of tornado genesis (23:01:52 UTC). EnKF Ensemble mean divergence (gray contours) and wind vectors at the lowest model level are overalain and the damage track of the El Reno tornado is outlined in blue. Relatively low values of ZDR (< 1.5 dBZ) south of the developing tornado are annotated as well as an internal reaf-flank downdraft (RFD) gust front that delineates the low Z_{DR} values from higher values.

27. Quantifying the Impact of Radar Data Assimilation in the Community Leveraged Unified Ensemble

Patrick Skinner (CIMMS at NSSL), Jamie Wolff, John Halley Gotway, and Randy Bullock (NCAR), Adam Clark (NSSL), and Ming Xue (CAPS)

Coordination between convection-allowing model (CAM) developers during the Spring Forecasting Experiments of 2016 and 2017 has resulted in the creation of a superensemble of CAM forecasts that can be used to conduct controlled experiments on ensemble design. Forecasts from this superensemble, known as the Community Leveraged Unified Ensemble, during the spring of 2016 were used to examine the impact of radar assimilation on CAM forecasts. Two 10-member ensembles, identical except that one ensemble assimilated WSR-88D data, were compared for 24 cases to identify the duration of impacts from radar data assimilation. A strong bias in simulated reflectivity was found to be present in members that did not assimilate radar data throughout much of the 36 hour forecast; however, similar coverage and skill was found between the two ensembles for rotation track forecasts. This suggests that assimilation of radar data has an indirect benefit in reducing the frequency bias for thunderstorm forecasts in convection-allowing models.

28. Coherent Airstream Analysis of an Idealized Supercell Simulation

Ryan Hastings (University of Connecticut), Patrick Skinner (CIMMS at NSSL), and Michael Coniglio (NSSL)

Agglomerative cluster analysis is being applied to sets of parcel trajectories calculated for an idealized supercell simulation in CM1 with 500 m horizontal grid spacing. The agglomerative clustering technique provides a method for objectively grouping like parcel trajectories in order to identify cohesive airstreams within the supercell. Six coherent airstreams are identified for parcel trajectories originating at low levels of the rear-flank downdraft. Of particular interest are two airstreams within an internal RFD momentum surge that occurs coincident with low-level mesocyclone intensification. One airstream originates 2-3 km aloft in the ambient environment and descends rapidly within the forward-flank precipitation shield of the supercell. A second airstream originates near the surface to the north of the developing mesocyclone. Trajectories within this airstream pass between the RFD surge downdraft and the mesocyclone, then wrap cyclonically around the mesocyclone and are ingested during intensification.

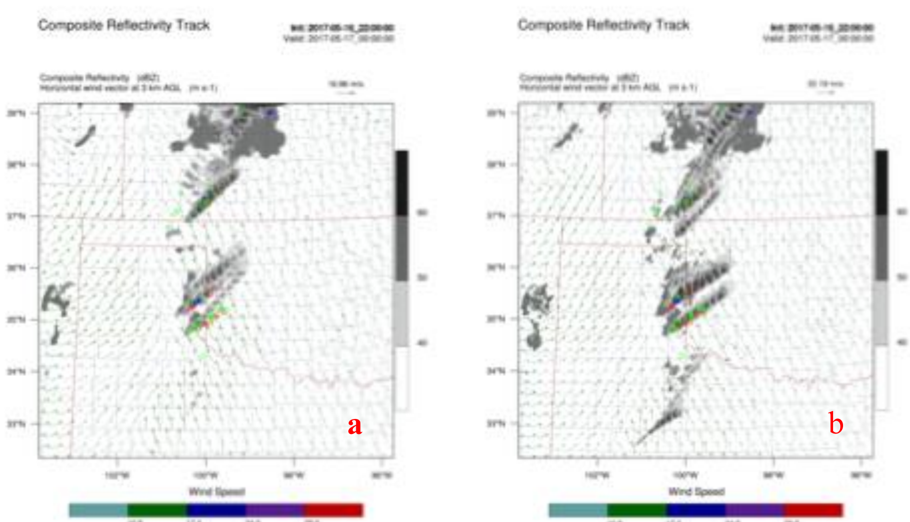
29. Development of a Weather-adaptive Hybrid 3DEnVAR and WRF-DART Analysis and Forecast Systems for Warn-on-Forecast

Yunheng Wang (CIMMS at NSSL) and Jidong Gao (NSSL)

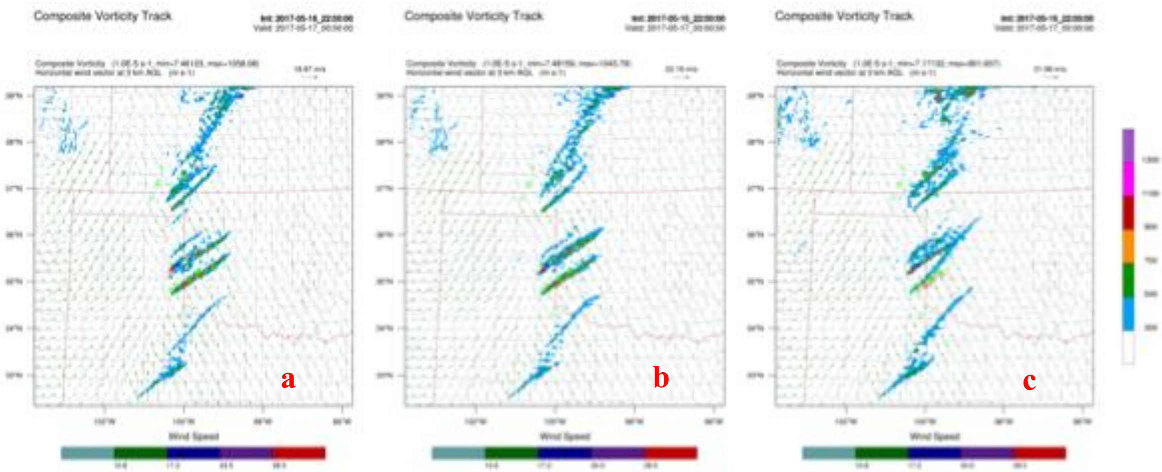
This is a continuous development of the real-time weather adaptive 3DVAR analysis and forecast system for the Warn-on-Forecast (WoF) project. This year, we extended the system capability to do 3DVAR ensemble analysis (3DEnVAR). It can now read WRF ensemble forecasts and compute flow-dependent covariance that will be combined with the static background error covariance at adjustable percentage. The system can conduct both one-way and two-way hybrid analysis with the NEWS-e system developed for WoF. With one-way hybrid scheme, the 3DEnVAR system incorporates available radar data, satellite retrieved cloud water path, and traditional soundings as observations, and ingests the ensemble forecasts from the NEWS-e system directly for deriving the flow-dependent background covariance. A hybrid gain data assimilation is included for a two-way hybrid scheme that combines the deterministic analysis from 3DEnVAR and the ensemble analysis from NEWS-e to produce a hybrid analysis around which the analysis ensembles are re-centered at each data assimilation cycle.

During the 5-week Hazardous Weather Testbed (HWT) Spring experiment period (May 1 – June 2 in 2017), we conducted real-time experiments with the one-way hybrid scheme aside with the NEWS-e experiments. Reasonable results are produced especially with the three major severe weather outbreaks on May 10, May 16, and May 25 respectively in 2017. Detailed results will be reported at the 38th Conference on Radar Meteorology. The 3DEnVAR system also has a capability to do dual-resolution analysis, i.e. when the ensemble forecasts are conducted at low resolution (3 km for NEWS-e), the deterministic analysis and forecast can be performed at higher

resolutions (1.5 km for HWT in 2017). The deterministic WRF forecast can be launched every 30 minutes from this physically-consistent analysis at high resolution. Sensitivity experiments have shown that high resolution helps in maintaining the storm strength and location accuracy during the forecasts (see first figure below). The second figure below shows preliminary results by comparing the 3DVAR-only analysis and forecast cycles with the hybrid run for a tornado outbreak case on May 16, 2017. It is found that 3DVAR-only analysis with radar reflectivity can maintain storm forecast strength but it has a large phase error. The ensemble-only analysis however, keeps the locations of the two major storms right especially during tornado outbreak, but with much weak strength. When combining the static covariance and the flow-dependent covariance together with a coefficient (α=0.6), forecasts for both the storm strength and location are improved.



Comparison of forecast reflectivity swath launched from (a) low resolution (3 km) analysis cycles at 2200Z on May 16, 2017 and that from (b) dual-resolution (1.5 km for deterministic analysis and 3 km for ensemble forecast) analysis cycles. SPC storm reports are denoted as red triangles for tornadoes, green diamonds for hails and blue filled triangles for high winds.

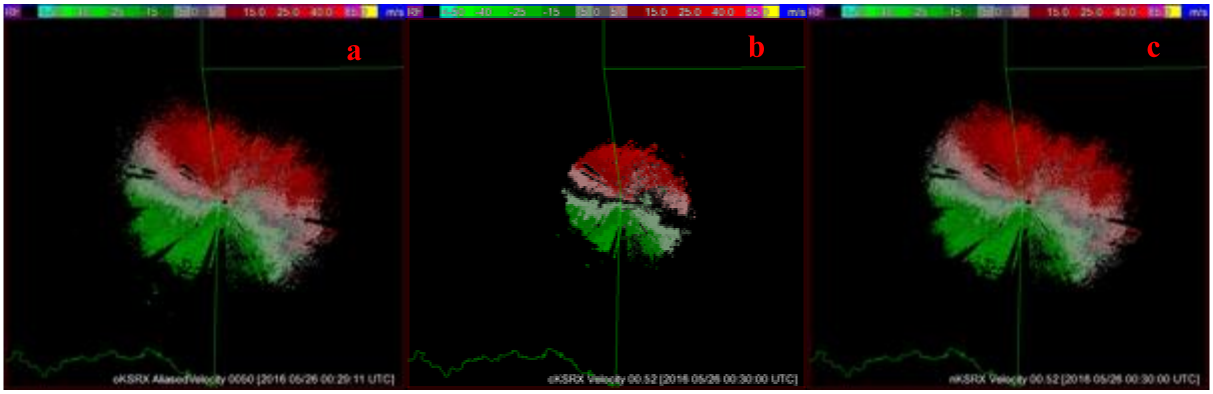


Forecast vorticity swath starting from 2200Z on May 16 to 0000Z on May 17, 2017. The WRF forecasts are launched (a) from 3DVAR-only analysis cycles (α=0.0) at 2200Z; (b) from 3DEnVAR hybrid analysis cycles with α=0.6; (c) from 3DEnVAR ensemble covariance only cycles (α=1.0). SPC storm reports are denoted as red triangles for tornadoes, green diamonds for hails and blue filled triangles for high winds.

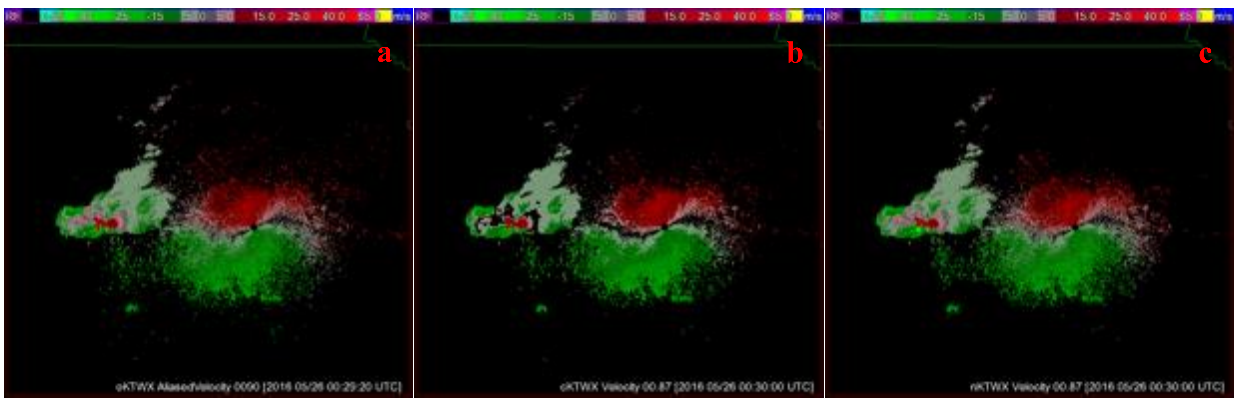
30. Real-time Application of the Model Based Robust-VAD Dealiasing Method for Processing Radar Observations

Yunheng Wang and Kang Nai (CIMMS at NSSL), and Qin Xu (NSSL)

The Model Based Robust-VAD De-aliasing Method for processing radar radial velocity has been proved valuable in several research papers. This method can get the alias-free radar radial wind field especially in severe weather situations. The cleaned radial wind fields can then be used on the wind retrieve analysis and data assimilation processing. The vortex parameters as a by-product can be used for further analyzing the vortex wind field around the observed tornado area. This method was just added to the 3DEnVAR system and it was optimized for real-time application. It will be tested further for values on severe convective storm forecasting within the WoF project. The figures below compare the robust de-aliasing method with the original one used in the 3DEnVAR system. The top figure shows radar observations that the robust method does keep more data than the old de-aliasing method. The bottom figure shows a case that the robust method can unfold data around a vortex area where the original de-aliasing method does not unfold.



(a) Radial velocity observations from radar KSRX; (b) unfold velocity using the original de-aliasing algorithm; (c) unfold velocity using the robust method. The new method keeps more valid data than the original method.



(a) Radial velocity observations from radar KTWX; (b) unfold velocity using the original method; (c) unfold velocity using the robust method. Velocity at the vortex area is unfold correctly.

31. Assimilation of Remote Sensing Observations into Convective-scale NWP to Improve 0-6 h Probabilistic Forecasts of High Impact Weather

Nusrat Yussouf, Junjun Hu, and Thomas Jones (CIMMS at NSSL), and David Turner (NOAA ESRL/GSD)

Accurate short-term (0-6 h) forecasts of hazardous convective weather (i.e. heavy rainfall, tornadoes, large hail and damaging winds) are crucial to reduce loss of life, property and disruption from high impact events. As part of NOAA's OWAQ FY16 Joint Technology Transfer Initiative, this research effort incorporates the ability to assimilate observations from ground-based remote sensing boundary layer instruments in the NOAA GSI-EnKF data assimilation system for more accurate model initial conditions with the goal to improve short-term forecasts of severe thunderstorms. The instruments include the Doppler Lidar that measures horizontal wind speed, direction and the Atmospheric Radiance Emitted Interferometers (AERI), that measures downwelling infrared radiation from which temperature and moisture profiles in the boundary layer up to ~ 3 km is retrieved. The forward operators for temperature and water vapor from AERI, u- and v-wind components from Doppler Lidar are incorporated into the data

assimilation system. The system is currently being tested using an EF3 tornadic event near Nickerson, Kansas on the evening of July 13, 2015 which is part of the Plains Elevated Convection at Night (PECAN) field campaign that took place from 1 June to 15 July 2015 in the Central Plains of the United States.

32. 0-6 h Extreme Convective Rainfall Forecasts Using a Prototype WoF System

Nusrat Yussouf and Thomas Jones (CIMMS at NSSL)

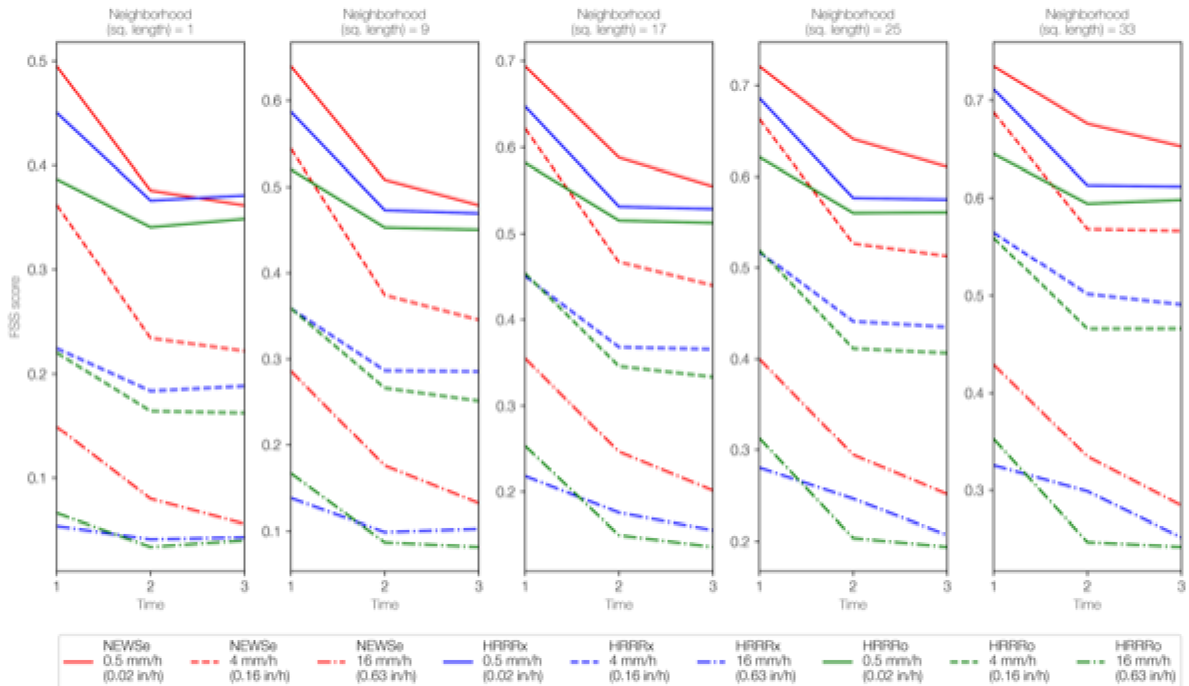
A prototype WoF system is developed using the WRF model and NOAA Community Gridpoint Statistical Interpolation (GSI), Ensemble Kalman filter (EnKF) data assimilation (GSI-EnKF) system. The system assimilates NWS conventional observations, WSR-88D reflectivity, radial velocity and geostationary satellite cloud water path retrievals. Retrospective 0-6 h probabilistic ensemble forecasts from several flash flood producing extreme convective rainfall events are generated using the frequent-update-cycle convective-scale ensemble data assimilation and forecast system. The performance of the system in predicting these events is evaluated using both qualitative and quantitative verification metrics.

33. Comparing Performance of NEWS-e During 2016 HWT with Operational HRRR Model

John Lawson and Nusrat Yussouf (CIMMS at NSSL), and Jack Kain (NSSL)

The real-time 3-h quantitative precipitation forecasts (QPFs) from a prototype WoF system, namely the NSSL Experimental WoF System for ensembles (NEWSe), are compared against those from two similar deterministic systems: the operational High Resolution Rapid Refresh (HRRR), and an upgraded, experimental configuration of the HRRR. All three model systems were run at 3-km horizontal grid spacing, and differ almost solely in the advanced data assimilation used by NEWSe. It is the impact of this difference that is evaluated using both traditional and scale-aware verification schemes.

The NEWSe, evaluated deterministically for each member, shows marked improvement over the HRRR configuration, especially at higher QPF thresholds and smaller spatial scales. This improvement diminishes with forecast lead time, reflecting the skill associated with an advanced data assimilation process. The next-generation HRRR model also provides added skill over its predecessor.



Fractional Skill Score (FSS) as a function of precipitation rate (line styles), model (color), and neighborhood size (increasing from left to right panels). Note the different y-axis limits between panels, as FSS asymptotes to unity as neighborhood size approaches the size of the domain. NEWSe (red lines) is the mean of the FSS values computed deterministically for each member. Higher FSS is better.

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NSSL Project 4 – Hydrologic Modeling Research

NOAA Technical Lead: Jonathan Gourley (NSSL)

NOAA Strategic Goal 2 – *Weather-Ready Nation – Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Task II

Objectives

Now that the Multi-Radar Multi-Sensor – Flooded Locations and Simulated Hydrographs (MRMS-FLASH) system has been demonstrated to be a useful tool for flash flood warning and that is running operationally at the National Centers for Environmental Prediction (NCEP), the focus has shifted to the development of probabilistic products within the Forecasting A Continuum of Environmental Threats (FACETs) framework. Objectives of this work are:

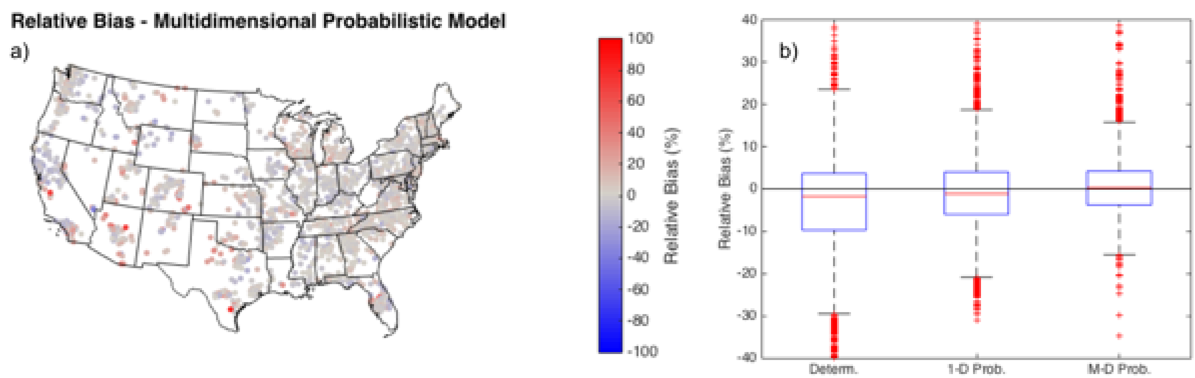
- To develop probabilistic models for the unit streamflow product in FLASH
- To develop a probabilistic model for flash flood impacts
- To evaluate FLASH's probabilistic products using Local Storm Reports (LSRs)

Accomplishments

1. Development of Probabilistic FLASH (Pro-FLASH) Products

J.J. Gourley (NSSL) and Humberto Vergara-Arrieta (CIMMS at NSSL)

Using the 10-year reanalysis of MRMS covering the 2002 – 2011 period, a probabilistic model for unit streamflow was developed via a multi-dimensional regression based machine learning approach. Besides enabling the capability to provide uncertainty information with every unit streamflow forecast, the probabilistic model yields bias-corrected estimates of unit streamflow. The figure below shows the assessment of biases from the multi-dimensional probabilistic model across the Conterminous United States (panel a) and a comparison with the deterministic and a simpler 1-dimensional probabilistic models (panel b). Work is ongoing to deploy this product for demonstration purposes on a real-time research environment.

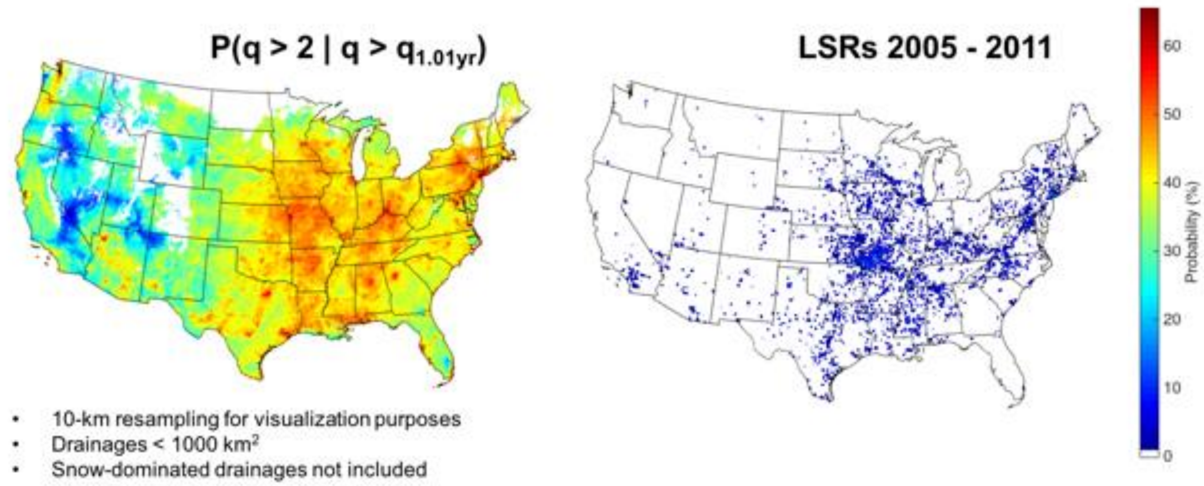


Evaluation of bias correction skill in probabilistic model for unit streamflow across the Conterminous United States: a) Map of bias at over 3,000 gauged locations; and b) Box plots of biases from all considered gauged locations for the deterministic model, 1-dimensional probabilistic model, and multi-dimensional probabilistic model.

2. Evaluation of Pro-FLASH Products with LSRs

J.J. Gourley (NSSL) and Humberto Vergara-Arrieta (CIMMS at NSSL)

An evaluation of the probabilistic estimates of unit streamflow was conducted using LSRs from 2005 – 2011. The analysis focused on drainages smaller than 1,000 km^2 and over areas with no significant snow contribution. The figure below shows a comparison of a time integrated probabilistic estimates of daily maximum unit streamflow values exceeding above-normal conditions and a space-time integrated summary of LSRs. Overall, the analysis demonstrates the ability of Pro-FLASH to provide useful background information for impact-based flash flood forecasts and risk assessment.



Comparison of FLASH-based probabilistic estimates of high unit streamflow values and flash flood LSRs for the 2005 – 2011 period: Probability of Exceeding 2 cms/km² given the 1.01 years Q has been exceeded any day during 2005 – 2011 ((Left); and, densities of flash flood LSRs within 10-km radius of a FLASH forecast point.

CIMMS Task III Project – Using Total Lightning Data from GLM/GOES-R to Improve Real-Time Tropical Cyclone Genesis and Intensity Forecasts

Alexandre Fierro (CIMMS at NSSL), Ted Mansell, Conrad Ziegler, and Don MacGorman (NSSL), Mark DeMaria (NOAA NCEP NHC), and Andrea Schumacher and Renate Brummer (CIRA-Colorado State University)

NOAA Technical Lead: Dan Lindsey (NOAA NESDIS)

NOAA Strategic Goal 2 – *Weather Ready Nation: Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Task III

Objectives

Conduct and subsequently utilize the output from cloud scale (250-m – 2-km) numerical simulations of the small-scale electrification processes within tropical cyclones (TCs) to augment our understanding on these processes and, ultimately, derive functional relationships between various lightning metrics and the microphysics/kinematics of TCs. Whenever possible, these relationships will be verified against (and complemented with) observations to ultimately develop total lightning predictors that could be used to assimilate total lightning observations directly into NHC's statistical prediction model (SHIPS). Total lightning is emphasized because it is much better correlated to convective strength than cloud-to-ground lightning is. Lightning information is particularly critical in regions where radar data are scarce, such as over oceans where all TCs develop and eventually intensify.

Accomplishments

The PI's visits to collaborators at CIRA and NHC and subsequent meeting of the PIs during the AMS Tropical/Hurricane meeting in April 2016 lead to the elaboration of a work plan for the remainder of the funding period. Namely, the results obtained in Fierro et al. (2015) during Year 1 needed be complemented with at least one TC lightning study in the idealized framework to help generalize/improve the functional relationships obtained in that study. With the help of the main developer of the NSSL fractal-like, stochastic 3D cloud electrification model (COMMAS) (Mansell), an idealized hurricane initialization/model based on Alex Fierro PhD work (Fierro et al. 2007) was successfully incorporated into this model over the course of Winter 2015. Over Spring 2016, several initial test simulations of idealized electrified TCs (on JET HPC resources) were conducted. The results motivated the inclusion of new physics along with improved vortex initializations [based on WRF-ARW]. Wind shear, relative humidity and sea surface temperature were varied using a base state substitution technique, which also was included into COMMAS (Mansell). With these model enhancements, realistic TC lightning behaviour and morphologies were obtained. The PI completed a manuscript draft during the course of Summer 2016 summarizing the results of three main simulations: Control (steady state major TC), a shear increase case and an SST cooling run. This study was accepted to JAS this Spring (Fierro and Mansell, 2017a). During the course of Spring 2017 a new, companion JAS manuscript (Fierro and Mansell, 2017b) was elaborated in which additional simulations/experiments focusing on intensifying TCs were analysed. As indicated in the conclusions of Fierro and Mansell (2017a), the focus on intensifying TCs was a logical follow-on because the three cases analysed in Fierro and Mansell (2017a) either were steady state or weakening TCs. This new study provides statistical analyses (correlations, linear regression, etc.) between different lightning metrics (flash extent density, flash origin density and source density) and various bulk microphysical and dynamic quantities within two key regions of the TC; namely the inner core and the rainband. Such analyses are of particular interest to NHC in the context of their statistical model called SHIPS (via the "RII" index). Results for the inner core are consistent with recent observational studies. Outer band convection, on the other hand, revealed being a far more difficult problem to tackle owing to its dependence on mesoscale/synoptic inhomogeneities that cannot be represented in idealized simulations or because of physics relevant to TC dynamics that are not included in COMMAS [such as PBL schemes, full radiation schemes, coupled ocean model]. Some preliminary tests were conducted with WRF-ARW [which features all of the above] but appeared to reveal similar biases [i.e., weaker-than-observed rainband convection]. Interestingly, no studies have addressed even partially this obvious bias because TC intensification is chiefly tied to inner core dynamics. In the light of this, it is very likely that ongoing work on this topic will continue beyond the funding period of this grant.

We organized a conference call with NHC in spring 2017 to synthesize the above results and, concomitantly, to discuss potential future collaboration on the subject. Emphasis was especially directed onto potential collaboration with NHC/CIRA regarding

to the analysis of GLM/GEOS-R total lightning data within observed TCs – which shall begin once the GLM instrument is fully calibrated and these data become available.

Publications

Fierro, A. O. and E. R. Mansell, 2017b: Relationships between electrification and storm-scale properties based on idealized simulations of an intensifying hurricane-like vortex**.** *Submitted to the Journal of the Atmospheric Sciences.*

Fierro, A. O. and E. R. Mansell, 2017a: Electrification and lightning in idealized simulations of a hurricane-like vortex subject to wind shear and sea surface temperature cooling. *Journal of the Atmospheric Sciences,* **74**, 2023-2041.

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CIMMS Task III Project – Ensemble Kalman Filter and Hybrid Data Assimilation for Convective-Scale "Warn-on Forecast"

Xuguang Wang and Yongming Wang (OU School of Meteorology)

NOAA Technical Lead: Pamela Heinselman (NSSL)

NOAA Strategic Goal 2 – *Weather Ready Nation: Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Task III

Objectives

To depict the internal structure of thunderstorms and to predict real tornadoes or tornado-like-vortices (TLV), sub-kilometer grid resolution is extensively applied to numerical weather predictions. Most of previous studies conducted a sub-kilometer forecast initialized from an analysis downscaled from storm scale analysis/forecast. Such downscaled analysis may be inadequate for the characteristics of sub-kilometer scales and its impacts on subsequent TLV forecast are still unclear. To resolve sub-kilometer scales, a sub-kilometer analysis should be directly produced within high-resolution data assimilation (DA). Past studies have demonstrated ensemble-based radar DA method can produce accurate analysis for convective scale predictions. However, running all background ensemble members at sub-kilometer resolutions in ensemble based DA may be prohibitive due to the extensive costs. Therefore, a GSI-based dual resolution EnVar system is proposed and implemented for direct assimilation of radar observations. Within this system, the analysis at a sub-kilometer resolution (hereafter true sub-kilometer analysis) is effectively produced whereas the lower-resolution ensemble is used to provide flow dependent covariances . Both downscaled and true sub-kilometer analyses are examined on the 8 May 2003,

Oklahoma City tornadic supercell case to understand their impacts on the evolution of tornadic supercell and embedded tornadoes during the subsequent forecasts.

Accomplishments

1. Introduction

In recent years, more and more studies (e.g., Xue et al. 2003; Dowell et al. 2004; Hu et al. 2006; Hu and Xue 2007; Jung et al. 2012; Dawson et al. 2012; Tanamachi et al. 2013; Yussouf et al. 2013; Thompson et al. 2015; Wang and Wang 2017) have made significant progress in the initialization and prediction of parent thunderstorms that spawn tornadoes. The high potential of tornado existence is obtained through successful prediction of tornadic supercell storm with strong mid- and low-level rotations at 1-3km grid spacing. However, Xue et al. (2014) stated directly forecasting tornado-scale circulations is more reliable than these modeled rotations, which are not correlated well with the strength and existence of tornado (e.g., Markowski et al. 2011; Marquis et al. 2012). Because of the small size of tornadoes, the spatial resolution (e.g., sub-kilometer) to resolve the tornado and its associated circulations should be much higher than what is needed to resolve the parent storm.

A few studies have simulated tornadoes or tornado-like-vortices (TLV) with a sub-kilometer resolution based on the real tornadic storms events. Mashiko et al. (2009) were able to produce a TLV in the simulation of typhoon Shanshan with a 50-m simulation initialized from a nested analysis within 5-km resolution forecast. Schenkman et al. (2012) employed three-dimensional variational data assimilation (3DVAR) cycles to initialize a mesoscale convective system (MCS) by assimilating radar and conventional observations on a 400-m grid and further launched a forecast on a nested 100-m grid. A detailed process of the tornadogenesis was provided on the 100-m simulation. Xue et al. (2014) predicted tornadoes on both 100-m grid and 50-m grid nested where DA was performed at 1-km resolution. The modeled tornado track is parallel to the observed tornado damage track but with 8-km northward displacement. Schenkman et al. (2014) documented the processes responsible for the tornadogenesis through studying the simulated tornadoes on the 100-m and 50-m grid initialized from 1-km and 100-m resolution forecasts, respectively. A similar study with 100-m and 200-m grid nested within a 2.2-km grid can simulate TLV using the Unified Model from Met Office (Hanley et al. 2016). The sensitivity of the TLVs to the microphysics schemes are also investigated by Dawson et al. (2015) utilizing a 250-m grid nested within a 1-km forecast. Most of the above TLV predictions with a sub-kilometer grid spacing are nested within a storm-scale grid, in which radar DA is conducted. However, few of these studies have attempted to resolve the sub-kilometer scales within the data assimilation. Most of their sub-kilometer forecasts are initialized from a coarser resolution forecast or analysis, which may lose the small-scale characteristics otherwise obtained during the data assimilation. The impacts of downscaling a coarser resolution analysis to a sub-kilometer grid on subsequent TLV forecast is unclear. Marquis et al. (2012) studied TLV associated circulations and mechanism for tornado maintenance using a 500-m EnKF analysis. However, the subsequent forecasts were not conducted in their study.

To resolve the sub-kilometer scales in analysis, a high-resolution data assimilation (true sub-km analysis) is required to provide a sub-kilometer analysis. Previous studies (e.g., Dowell et al. 2004; Tong and Xue 2005; Jung et al. 2008; Lei et al. 2009; Dowell et al. 2011; Yussouf et al. 2013; Johnson et al. 2015; Wang and Wang 2017) have demonstrated that ensemble-based methods by assimilating radar observations can provide accurate analysis to well predict the thunderstorms. Due to the expense of running sub-kilometer background ensembles, directly extending such ensemble based DA methods for sub-kilometer analysis may be prohibitive. In this study, a new dual resolution (DR) EnVar system is implemented to produce the analysis at a sub-kilometer grid where a high resolution (HR) background and analysis are produced (e.g., sub-kilometer) with a low resolution (LR) background ensemble, avoiding the need of a costly HR ensemble. The new method is developed with the reflectivity as the state variable based on the direct radar data assimilation method proposed by Wang and Wang (2017). The new DR EnVar system is applied on the analysis and prediction of the 8 May 2003, Oklahoma City (OKC), tornadic supercell storm. We primarily focus on practical respects regarding the impacts of downscaled and true sub-km analyses on subsequent TLV simulations, e.g., understanding their influences on mechanism of tornado maintenance.

2. Event Overview and Experiment Methodology

a. Overview of Tornado Outbreak

The OKC tornadic thunderstorm has been introduced in Romine et al. (2008), Hu and Xue (2007), and Wang and Wang (2017). An isolated supercell with a pronounced hook appendage is found at around 2200 UTC. The supercell storm propagated east-northeastward, and began to weaken after 2300 UTC, and dissipated by 0020 UTC 9 May. The segmented paths produced by its spawned tornadoes are shown in Fig. 1. As the official NWS survey results, two tornadoes are found from 2204 to 2238 UTC. A F0/F1 tornado persisted from 2204 to 2208 UTC in southwest of Moore tracked on the ground for about 3-km. Within the same storm, another widespread F2-F4 damage tornado formed at 2210 and dissipated at 2238 UTC with a ~30-km east-northeast track path.

b. Data Assimilation and Experiment Design

The experiments in this study are produced with version 3.6.1 of the nonhydrostatic Advanced Research WRF (WRF-ARW, hereafter WRF; Skamarock et al. 2008) over a nested domain spanning most of Oklahoma state (Fig. 2). The horizontal grid spacing is 2 km (226 × 181 grid points) in the outer domain and 500 m (361 × 281 grid boxes) in the inner nest. Both domains are configured with 50 vertical levels and a 50-hPa top.

Similar with Wang and Wang (2017), a 2-km resolution analysis is produced with GSI-based EnVar data assimilation (DA) system by assimilating radar observations to serve as a benchmark, named as SR system. To effectively produce true sub-km analysis, a

GSI-based dual-resolution (DR) EnVar method is implemented for WRF- ARW. Such method can produce sub-km analysis by ingesting lower resolution ensembles. Its detailed algorithms are similar to Schwartz et al. (2015). The procedure of radar data assimilation and subsequent forecast for both systems are shown in Fig. 3. Starting at 2100 UTC 8 May 2003, the radar data are assimilated every 5 minutes for a 1-h period out to 2200 UTC. One-hour forecasts are then launched from the control analysis initialized at 2200 UTC. The analysis at 2200 UTC in the SR system is firstly downscaled to 500-m resolution and then advanced for 1-hour lead time to produce TLV forecasts.

The true and downscaled sub-km analyses respectively produced by the above SR and DR EnVar system are used to investigate their impacts on subsequent TLV simulations in Exp-SR and Exp-DR. During the data assimilation cycles, multiple fields are updated, e.g., dynamic (U, V, W), thermodynamic (T) fields and hydrometeor mixing ratios. To understand the role of each type of fields on the TLV simulations, 4 additional experiments are conducted by replacing one type of fields in downscaled sub-km analysis with what in true sub-km analysis. Specifically, Exp-Hydro is conducted by replacing hydrometeor mixing ratios, including rainwater, ice, graupel, and cloud-water mixing ratios; The horizontal and vertical wind (U, V, and W) fields and temperature (T) field are respectively changed in Exp-UVW and Exp-T; Exp-UVWT launch a forecast initialized from an analysis of Exp-SR with both dynamic and thermodynamic fields being replaced.

3. Results

a. The Evolution of Predicted Tornadoes

To evaluate the impacts of downscaled and true sub-km analyses on the TLV forecasts, we verify these forecasts against the observed tornado damage paths (Fig. 1). The simulated tornado paths are represented by taking the maximum surface vorticity from entire forecast period (Figs. 4a, b). The vertical vorticity near ground in Exp-SR (Fig. 4a) reaches relatively strong magnitude (greater than 0.025 s^{-1}) in ~5-min forecast and fits well with the observed tornado path in the early stage of forecast. However, this strong surface rotation persists for ~15-min and weakens after the 18-min forecast. The evolution of simulated rotation in the later stage forecast deviates the observations. The surface vorticity simulation initialized from true sub-km analysis includes two strong segmented swaths (Fig. 4b). Both the timing and locations of these swaths agree well with the evolution of observed tornado. The first strong simulated vorticity begins at ~3-min forecast lead time and weakens after 4 minutes. At ~22:10 UTC, the re-intensified vorticity is produced and persists for ~24 minutes.

The contributions to the variation of vertical vorticity can be resolved into advection, stretching and tilting terms in the vertical vorticity equation. Figures 4c and 4d show the three terms within a 1-km horizontal distance of the peak vertical vorticity during the entire forecast period in Exp-SR and Exp-DR. Near the ground, the magnitude of stretching term is much larger than that of advection and tilting terms and the resolved vertical vorticity maxima most closely follow the maxima in stretching term in both

experiments. Therefore, the evolution of near ground vertical vorticity depends on the horizontal convergence near the vorticity maximum.

The scales of simulated tornadoes measured by the maximum surface wind speed are also verified. Their distributions during the entire forecast period at each point for Exp-SR and Exp-DR are plotted in Figs. 4e and 4f. Wind speed maxima exceeding 29 m s^{-1} is produced in Exp-SR, indicating a F0 intensity tornado. The 2nd tornado in reality is not predicted in Exp-SR. Meanwhile, 2 tornadoes are produced in Exp-DR, the 1st F1 intensity tornado with a maximum wind speed of ~39 m s^{-1} and the 2nd tornado with F0 intensity scale. The simulated strength of the tornado is significantly weaker than the observed F4 tornado; this is most likely due to insufficient resolution (Hanley et al. 2016). Similar studies with finer resolution will be left for future studies. It seems that the strength of simulated tornadoes is correlated well with the intensity of vertical vorticity in both experiments. The second segmented tornado produced in Exp-DR are highly correlated to its re-intensified vertical vorticity in the later forecast.

b. Mechanism of Tornado Maintenance

The largest differences of simulated vortices between Exp-SR and Exp-DR lie on re-intensified vortices in the later stage of the forecast in Exp-DR. Since the evolution of simulated vortex is determined by the horizontal convergence as stated in section 3a, we present its circulations in Fig. 5 and Fig. 6 for Exp-SR and Exp-DR, respectively. The forecast times of 15-, 18- and 21-min are chosen in Fig. 5 as vertical vorticity of Exp-SR gets weakened from peak vertical vorticity during this period (15-21 min). As stated by Dowell and Bluestein (2012), an area underneath the midlevel updraft is the ideal location of tornado maintenance. Therefore, such structure that low-level convergence surrounding the tornadoes provides the inflow to the midlevel updraft can favor the development and maintenance of tornadoes. In 15-min forecast, Exp-SR has strong surface vertical vorticity with surface vorticity correlated well with updraft locations aloft (Fig. 5a). After 3 minutes, the surface vorticity is weakening as the tilt of mesocyclone increases (Fig. 5b) and the low-level mesocyclone-scale convergence is replaced with divergence by eastly cold pool outflow (Fig. 5c). Such condition is further enhanced in 21-min forecast (Fig. 5e) and the mid-level updraft is fueled by ambient inflow that rises along the rear flank gust front rather than tornado associated circulations (Fig. 5f). The process of re-intensifying vorticity from 15-21 min for Exp-DR is presented in Fig. 6. The maintenance of tornado in Exp-DR coincides with a tornado located beneath the midlevel updraft. The low-level convergence around tornado can provide inflow to midlevel updraft; meanwhile strong western outflow with divergence is approaching the vertical vorticity maximum (Figs. 6a, b). Fortunately, relatively warm secondary outflow favors the development of the secondary gust fronts near the tornado (Fig. 6c). Such warm secondary outflows have been observed in certain mobile mesonet studies (e.g., Fineley and Lee 2008; Finely 2010 et al. 2010; Markowshi et al. 2012) and may result from descending air parcels overshoot their equilibrium level (e.g., Johnson 1983). The secondary gust fronts provide additional low-level convergence near the tornado (Fig. 6e). Additionally, the positively buoyant air originating in the secondary downdraft feeds a band of ascent along the secondary gust front (Fig. 6f). Therefore, it appears that the developed secondary gust fronts due to the warm

downdraft surge determines the re-intensified vertical vorticity. Relative to Exp-SR, the re-intensified vorticity in Exp-DR may be caused by the existence of secondary gust fronts.

A surface pressure minimum is accompanied with the structure that a low-level convergence beneath the midlevel updrafts. Since such low pressure occurs in the inflow region of tornadoes, flow can accelerate toward the updraft base. According to Markowski and Richardson (2010), the pressure drop Δp associated with inflow accelerations can be given as, where υ is the wind speed near the tornado vortex and υ_0 is the wind speed far from

$$\Delta p=\frac{\rho}{2}(\upsilon^2-\upsilon_0^2), \quad (1)$$

the vortex. For $\rho \sim 1$ kg/m^3, inflow can accelerate from 15 to 41 m/s with an inflow low of 2 hPa, e.g., DR at 15- and 18-min and SR at 15-min (Figs. 7a-c). For SR at 18-min forecast (Fig. 7d), inflow can be only increased from 15 to 18 m/s with an inflow low of 0.5 hPa. The maximum wind speed distributions in Figs. 4e and 4f can be explained here. The second tornado can be produced in Exp-DR due to the persisted horizontal convergence, which can favor the maintenance of vertical vorticity.

c. Impacts of Analysis Fields on Tornado Evolution

Downscaled and true sub-kilometer analyses produce significantly different evolution of tornadoes. A comparison between the two analyses is shown in Fig. 8. At the analysis time, Exp-DR produces stronger cold pool than Exp-SR (Figs. 8a, b). In the upper layer, similar magnitude of reflectivity distributions is shown in both experiments but greater updraft and downdraft are found in Exp-DR than Exp-SR (Figs. 8c, d). Since several variables are different in Exp-SR and Exp-DR, it is difficult to distinguish the influences of each kind of variables on the evolution of simulated tornadoes. To determine the sensitivity of analysis fields to subsequent forecasts, 4 additional experiments introduced in section 2b are conducted.

The evolutions of vertical vorticity in 4 experiments are investigated first. Exp- Hydro (Fig. 9a) produces similar vorticity track with Exp-SR. Strong vorticity begins at ~5 min and weakens at ~18 min. Exp-UVW (Fig. 9b) has two segmented vorticity paths. The first path is similar with that in Exp-DR and the vorticity is re-intensified after ~3-min but with a weaker vorticity and a shorter lived second swath than Exp-DR. Similar simulated tornado swaths with Exp-DR are reproduced in Exp-UVWT (Fig. 9c), not only its intensity but also the longevity. Although 2 tornado paths are simulated in Exp-T (Fig. 9d), the timing of vorticity deviates far away from observations. The first path in Exp-T seems more like the one in Exp-SR.

As the vorticity evolutions are various for 4 different experiments in the later stage of forecasts, we present the evolution of cold pool and low-level gust fronts in the periods with weakening vorticity for Exp-Hydro and re-intensifying vorticity for Exp- UVW, Exp-UVWT, and Exp-T in Fig. 10. Similar with Exp-SR, the demise of simulated tornado in

Exp-Hydro coincides with a separation from the midlevel updraft and increasing divergence from western surge of the outflow surrounding tornadoes (Figs. 10a, b). Since the similar magnitudes of hydrometeor mixing ratios (Figs. 8c, d) are obtained in the analyses of Exp-SR and Exp-DR, the impacts of structure distributions of hydrometeor mixing ratios on the tornado simulation can be considered as a non-determined factor with a certain magnitude of reflectivity. The role of dynamic fields in the analysis on the tornado simulation is investigated through a comparison between Exp-SR and Exp-UVW. The re-intensifying process from Exp-UVW is shown in Figs. 10c and 10d. A significant difference between Exp-SR and Exp-UVW is the secondary gust fronts, which may assist tornado maintenance by baroclinically generating and then tilting horizontal vorticity in the secondary outflow. Exp-T can help to understand the influence of cold pool at analysis time on tornado simulation (Figs. 10e, f). The simulated vertical vorticity can be re-intensified in spite of a delay. Comparing with Exp-SR, Exp-T produce stronger and more widespread cold pool in the entire forecast lead time. Since the evolution of cold pool is an accumulated process, cold pool can develop more faster with a stronger initial cold pool. Thus, gust fronts can move more forward in Exp-T, especially for rear flank cold pool. The magnitude of cold outflow air is weakening as it is approaching the tornadoes and therefore the convergence surrounding the tornadoes cannot be easily replaced in Exp-T. In addition, the rear flank gust fronts can even tilt the horizontal vorticity with the outflow to help tornado maintenance. Exp-UVW and Exp-T indicate that both mesocycle dynamic and thermodynamic fields can determine the motion of tornado. Exp-UVWT by combining Exp-UVW and Exp-T produces a tornado close to Exp-DR and observations (Figs. 10g, h). Relative to Exp-UVW, a stronger cold pool analysis can favor the production of a more widespread and stronger cold pool in later forecast in Exp-UVWT and Exp-DR. In Exp-UVW, the air between primary and secondary gust fronts is warmer than that in rear of secondary gust front. Therefore, the negatively buoyant air may be difficult to ascent along the secondary gust front, and thus leading to a shorter lived second swath in Exp-UVW than Exp-UVWT.

According to these experiments, we speculate the timing of re-intensified vorticity depends on the mesocyclone dynamic fields; while the strength and longevity of re-intensified vortex rely on the strength of cold pool at the analysis time. A realistic tornado structure can be obtained by advancing the true sub-km analysis from the dual-resolution EnVar radar DA system. The sub-km analysis downscaled from storm-scale analysis loses small scale perturbations for dynamic characteristics and underestimates thermodynamic characteristics adapting to sub-kilometer scales.

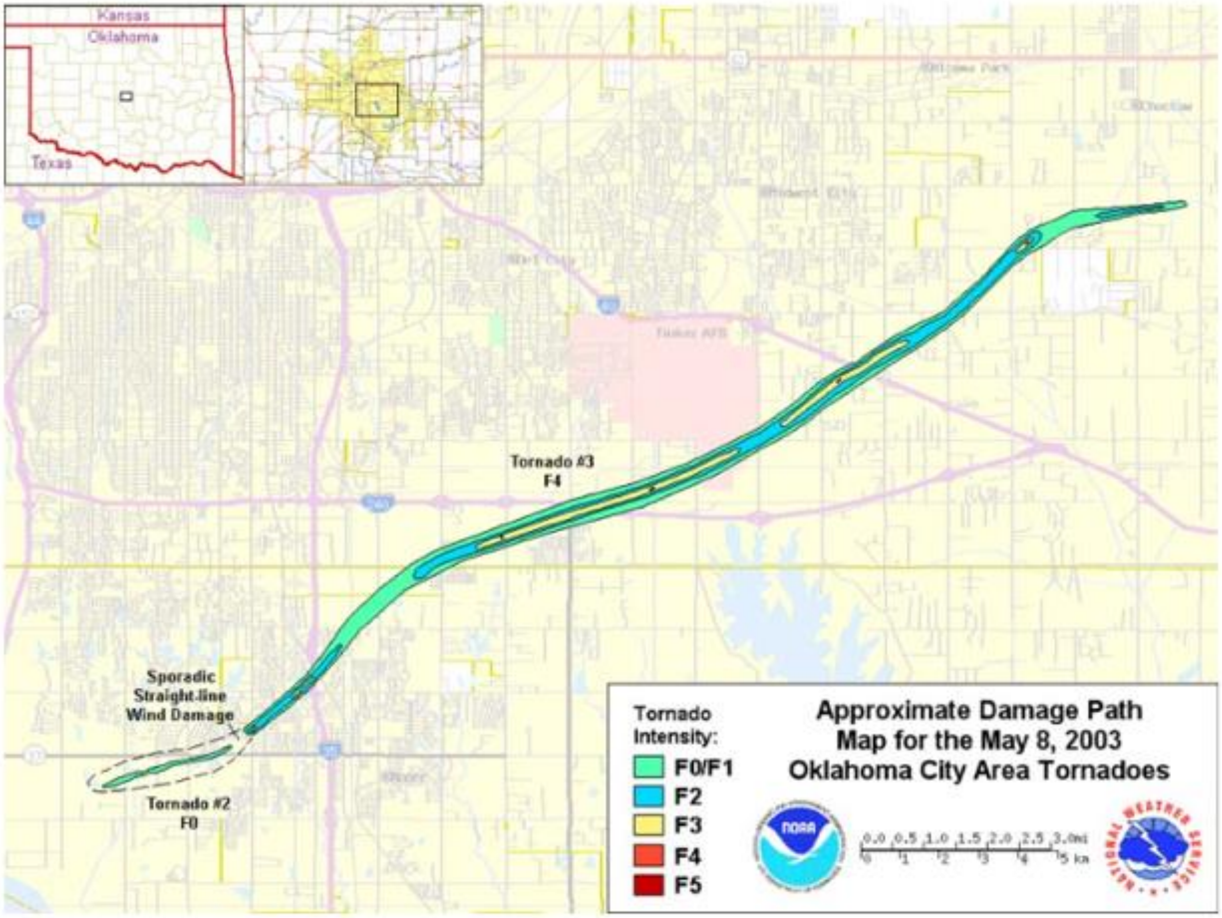


Fig. 1 Map of the southern Oklahoma City area overlaid with the track of the observed tornadoes on 8 May 2003. Image is adapted from the Norman, OK, National Weather Service (NWS) website: http://www.srh.noaa.gov/oun/?n5events-20030508*.*

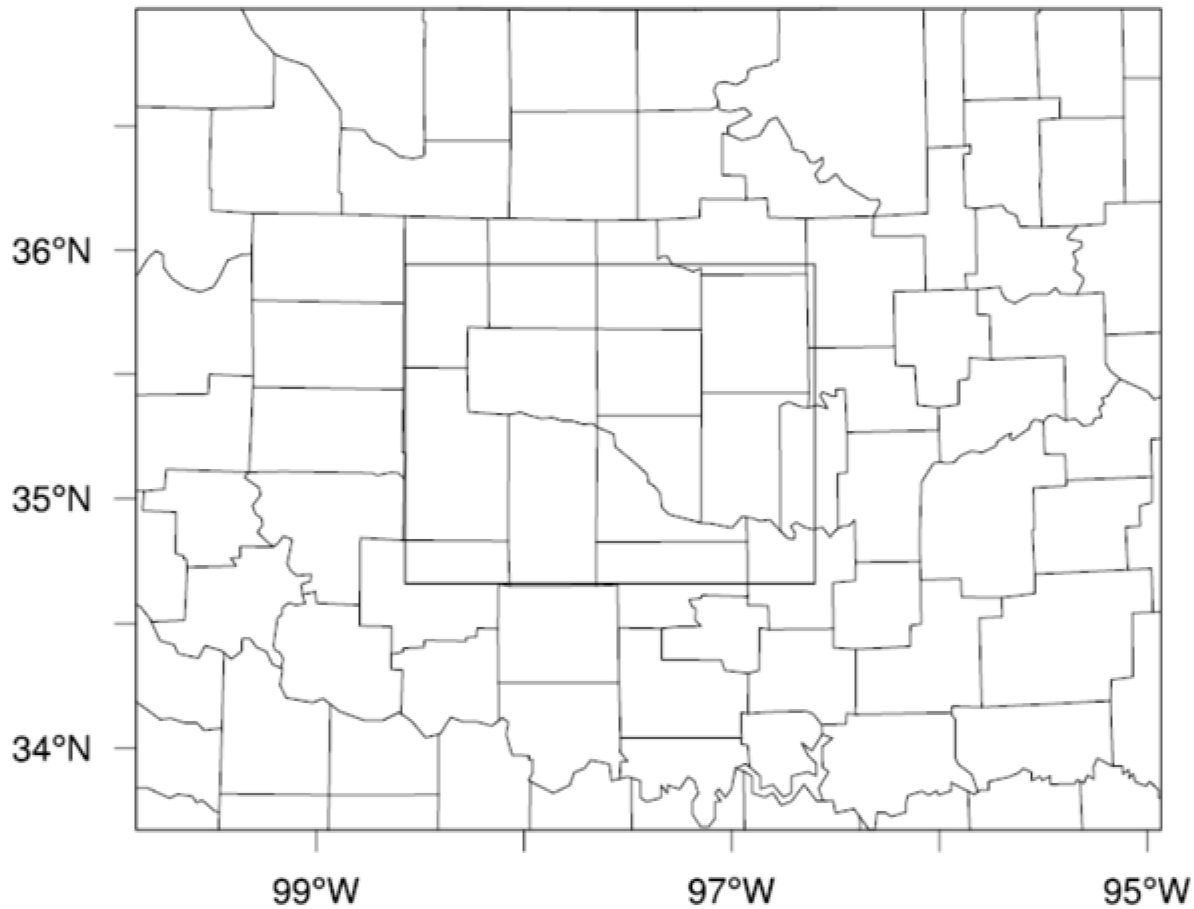


Fig.2 The outer domain with a 2-km grid for the ensemble and the control in the single-low-resolution EnVar and the inner domain with a 500-m resolution for the control in the dual resolution EnVar.

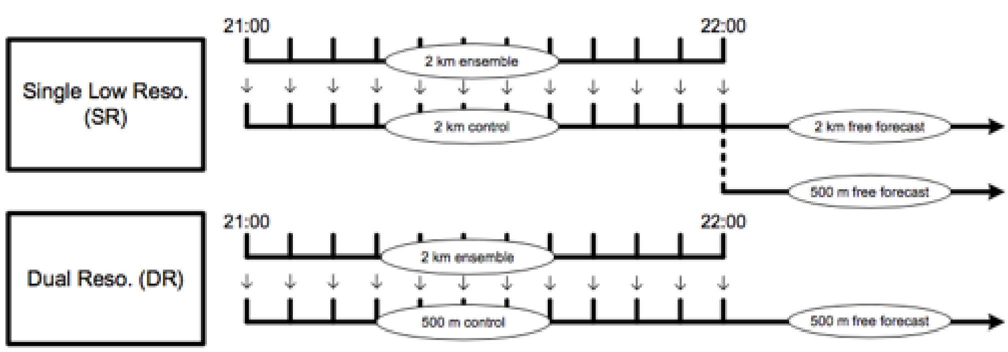


FIG. 3 Schematics of data assimilation experiment configuration. The radar data assimilation adopts the 5-minute cycling and the flow-dependent error covariance is provided by the 2-km resolution ensemble forecasts in both SR and DR EnVar. All 1-hour forecast at 500-m resolution is then initialized by the analysis at 2200 UTC after 1-hour assimilation.

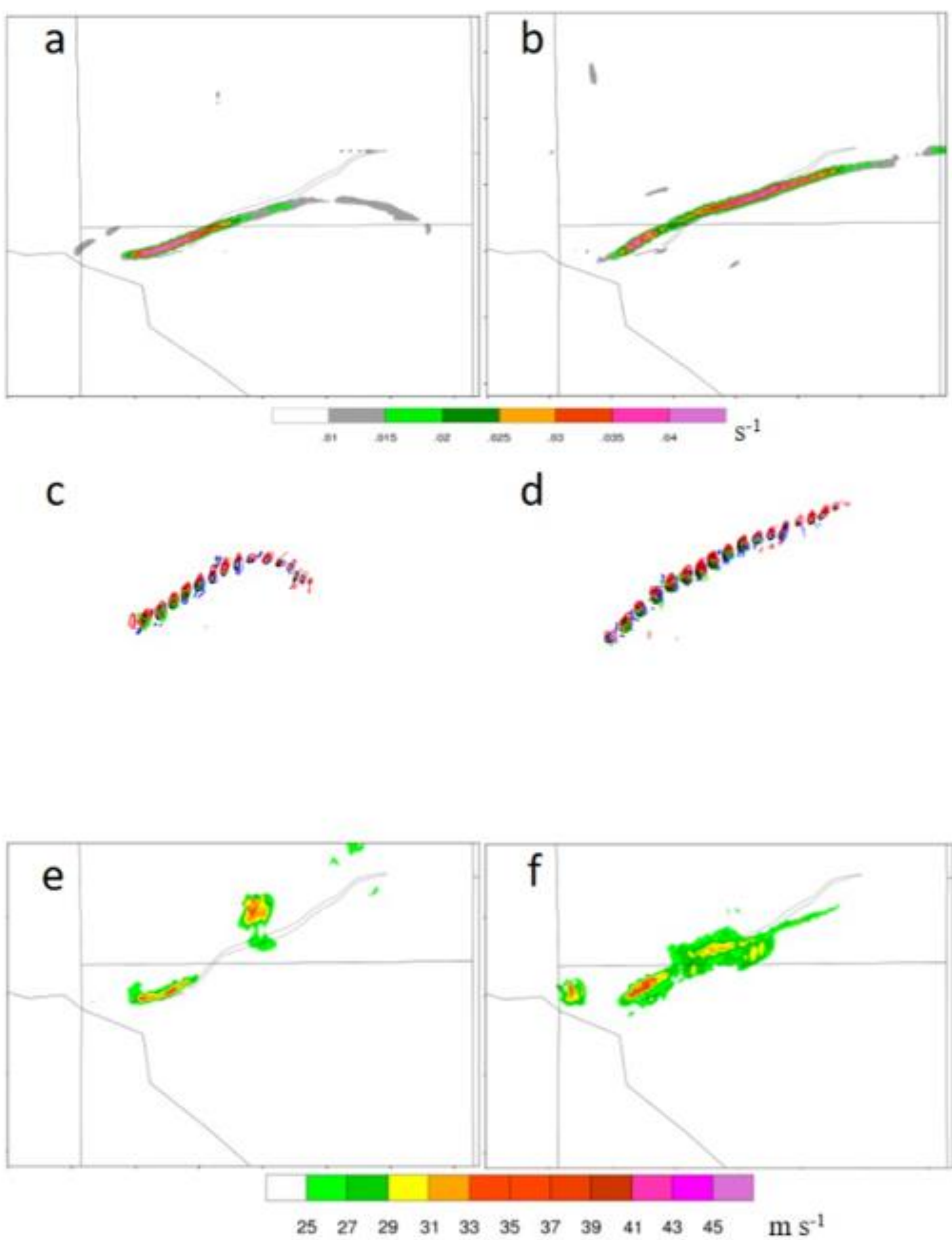


Fig 4. (a), (b) Composite maximum surface vorticity (constructed by taking the maximum of the filed from all output times; s-1) swaths, in shaded contours, for the period 2200-2300 UTC (3600-s model time, 60-s interval) for (a) Exp-SR and (b) Exp-DR. (c), (d) Peak vertical vorticity (black contours) and the positive maxima of the advection of vertical vorticity (blue contours), stretching (red contours) and tilting (green contour) of vertical vorticity within a 1-km horizontal distance of the tornado every 3-min for the period 2200-2300 UTC for (c) Exp-SR and (d) Exp-DR. (e), (f) Composite maximum surface wind speed swaths for period 2200-2300 UTC for (e) Exp-SR and (f) Exp-DR. The overlaid lines in (a), (b), (e), and (f) is the observed tornado track for reference.

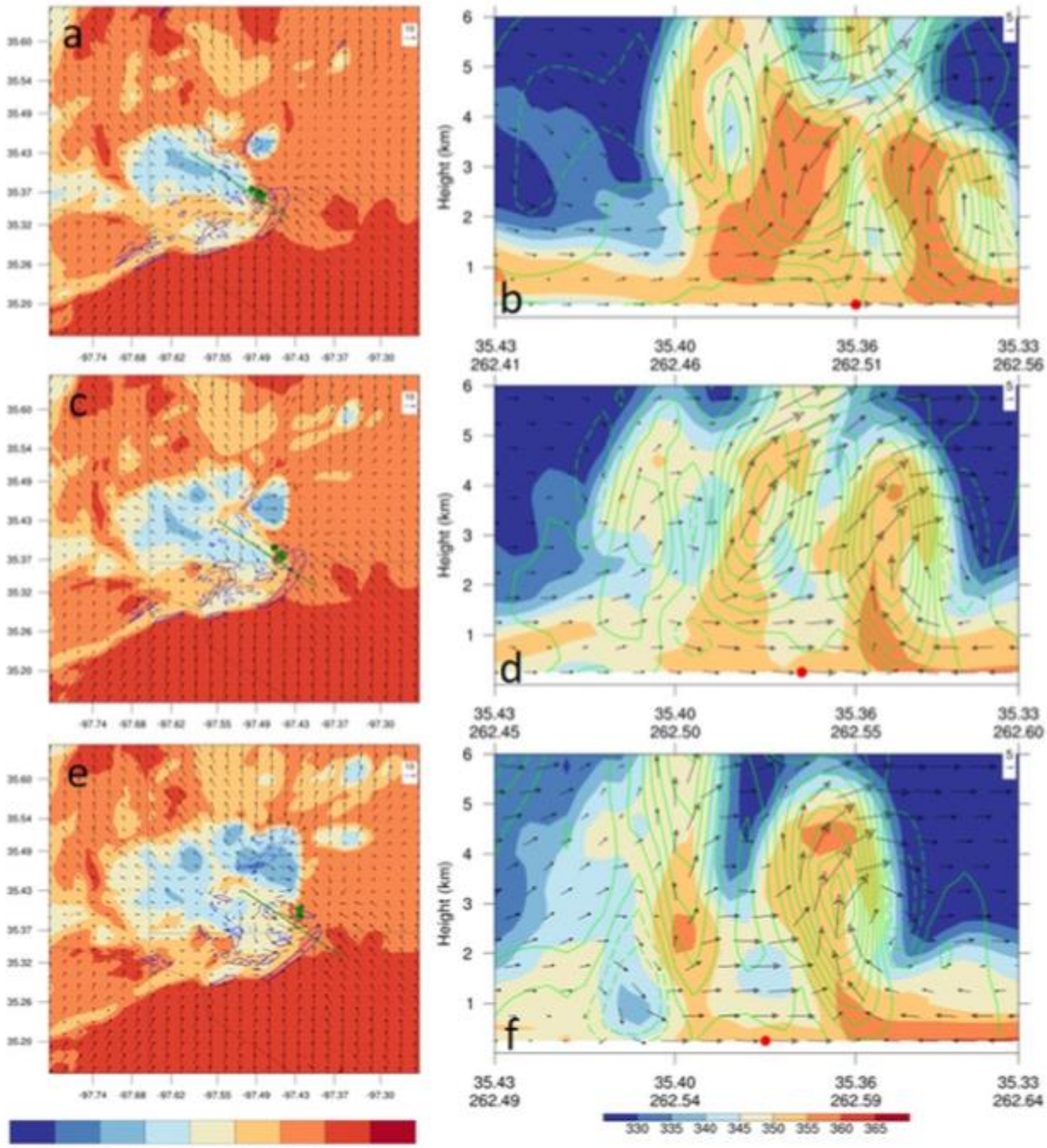


Fig. 5 Equivalent potential temperature (shaded, K), wind vectors (m s-1), and vertical vorticity (black contours, starting at 0.01 s-1) at 1st model level at (a), (b) 22:15, (c), (d) 22:18, and (e), (f) 22:21 UTC 8 May 2003 for Exp-SR. Vertical cross sections of the same fields along the green line in (a), (c), (e) are shown in (b), (d), (f), respectively. The red circles in (b), (d), (f) are denoted as tornado locations.

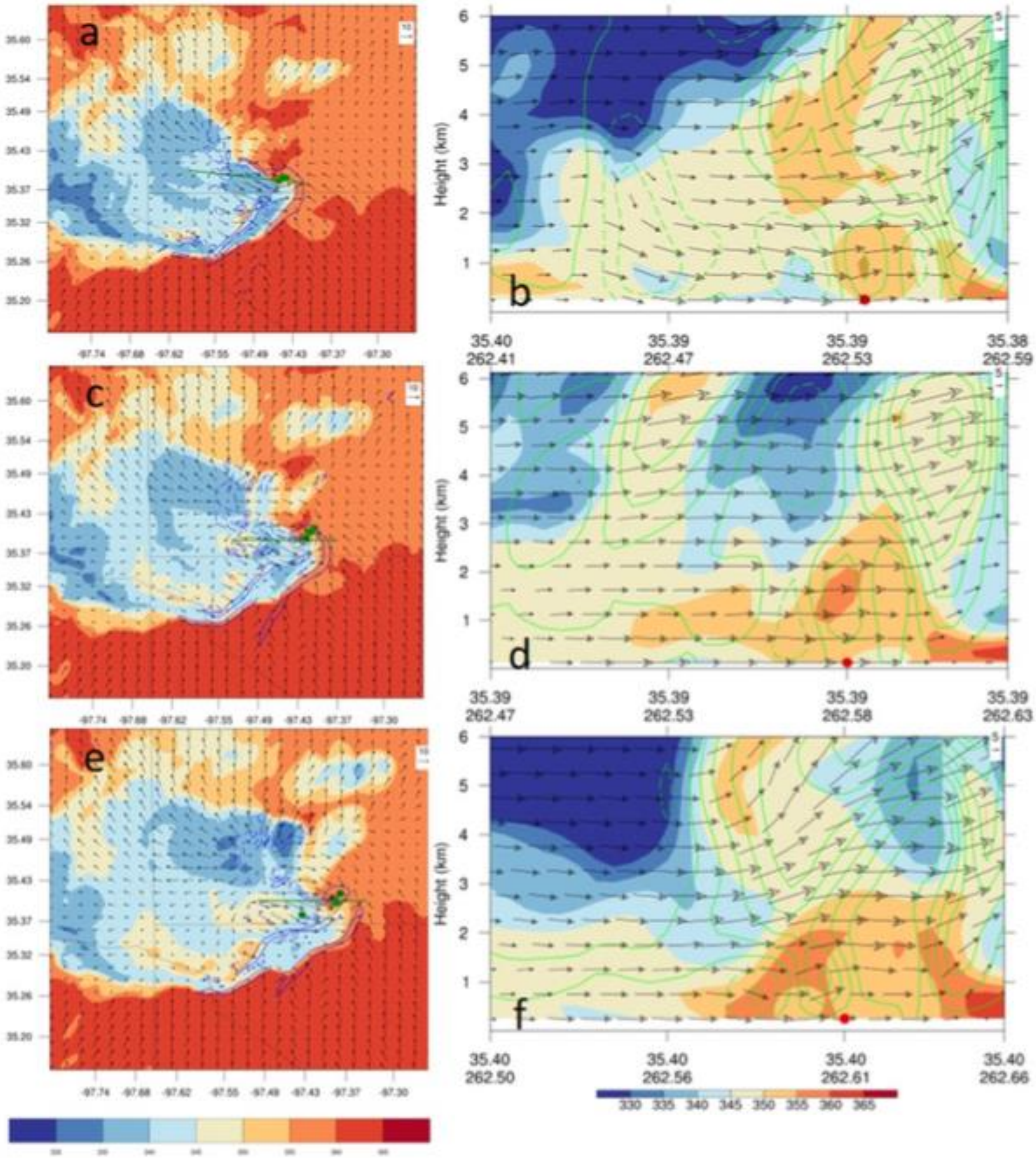


Fig. 6 Same as Figure 5, except for Exp-DR.

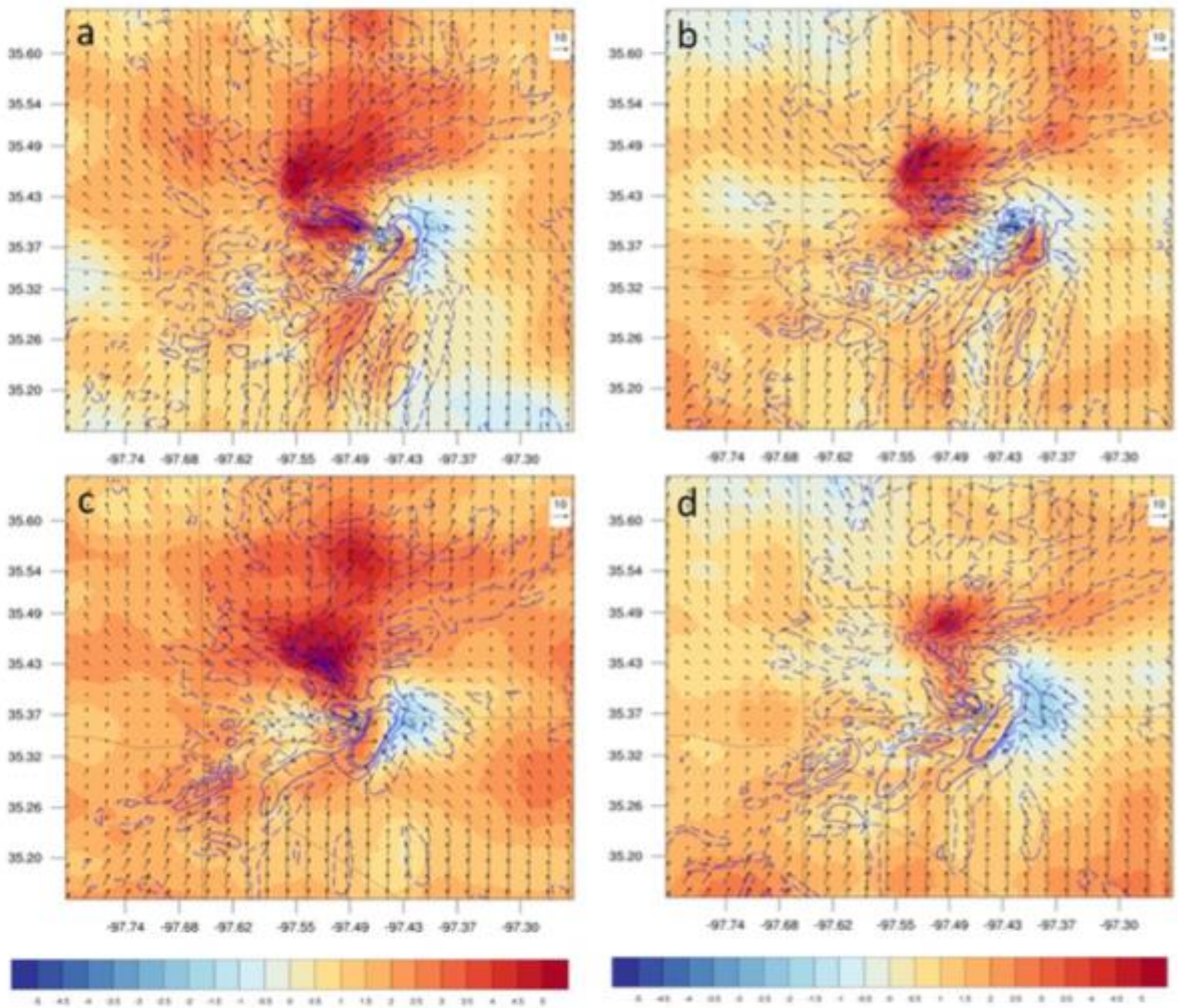


Fig. 7 Perturbation pressure (shaded; hPa), wind (vector; m s-1) at 1st model level and vertical velocity (blue contours; m s-1) at 1km AGL at (a), (c) 22:15 and (b), (d) 22:18 UTC for Exp-SR (a, b) and Exp-DR (c, d).

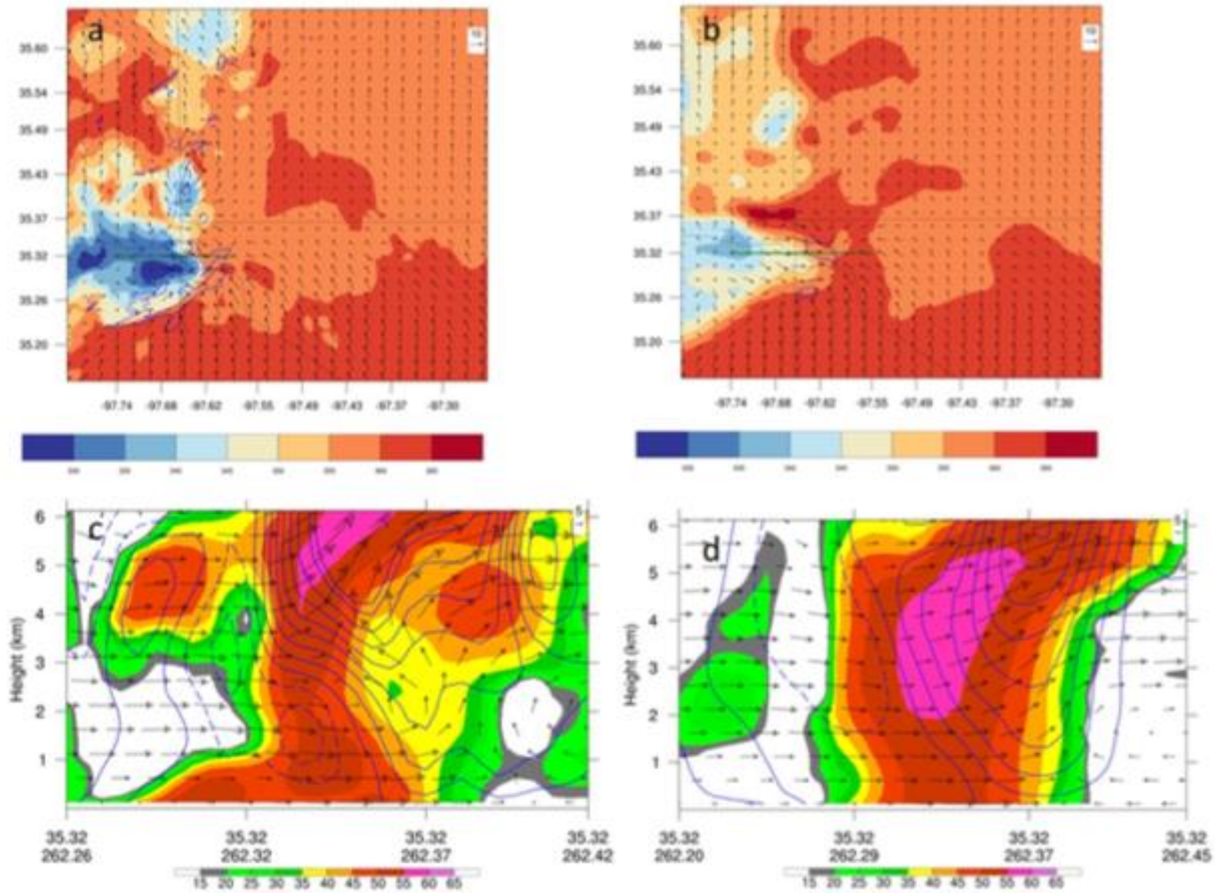


Fig. 8 Equivalent potential temperature (shaded, K), wind vectors (m s-1), and vertical velocity (blue contours, m s-1) at 1st model level at analysis time for Exp-DR (a) and Exp-SR (b). Vertical cross sections of the same fields along the green line in (a), (c) are shown in (b), (d), respectively. Reflectivity (shaded, dBZ), vertical velocity (blue contours, m s-1) for Exp-DR (c) and Exp-SR (d) at analysis time.

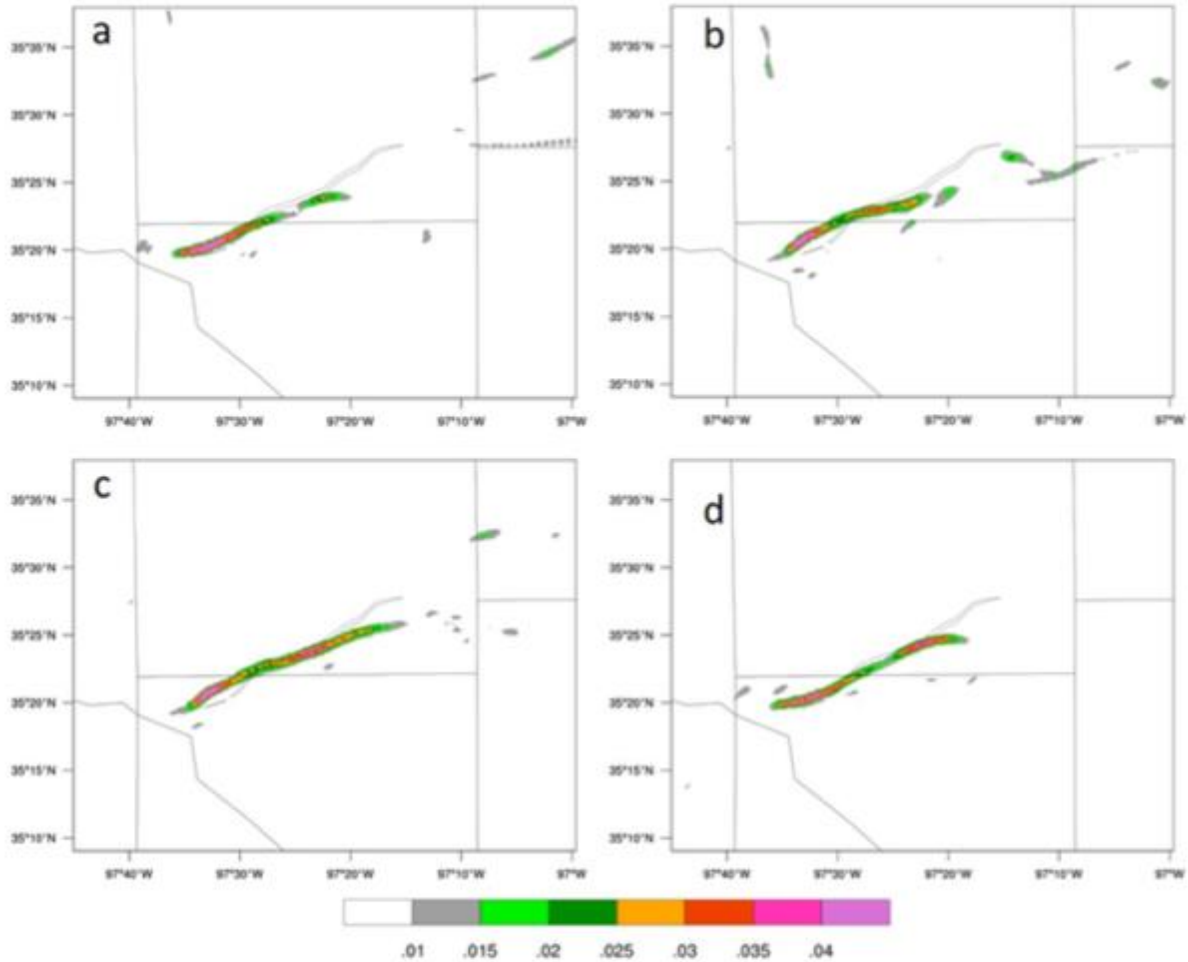


Fig. 9 Composite maximum surface vorticity swaths, in shaded contours, for the period 2200-2300 UTC (3600-s model time, 60-s interval) for (a) Exp-Hydro, (b) Exp-UVW, (c) Exp-UVWT, and (d) Exp-T.

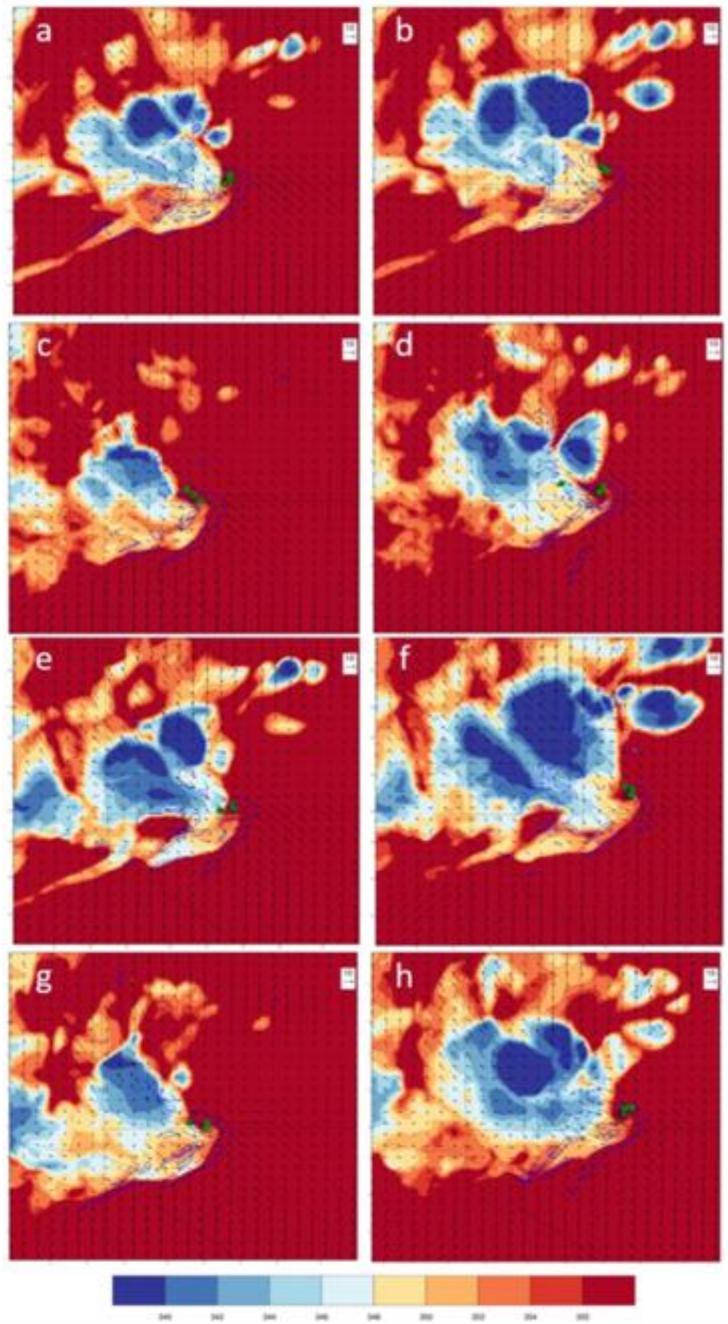


Fig. 10 Equivalent potential temperature (shaded, K), wind vectors (m s-1), and vertical velocity (blue contours, m s-1) at 1st model level at (a) 22:18, (b) 22:21 for Exp-Hydro, (c) 22:09, (d) 22:12 for Exp-UVW, (e) 22:13, (f) 22:15 for Exp-UVWT and (g) 22:18, (h) 22:24 UTC for Exp-T.

Publications

Wang, Y. and X. Wang, 2017: Direct Assimilation of Radar Reflectivity without Tangent Linear and Adjoint of the Nonlinear Observation Operator in GSI-Based EnVar System: Methodology and Experiment with the 8 May 2003 Oklahoma City Tornadic Supercell. *Monthly Weather Review*, **145**, 1447-1471. https://doi.org/10.1175/MWR-D-16-0231.1.

Theme 3 – Forecast and Warning Improvements Research and Development

NSSL Project 6 – Development of Technologies and Techniques in Support of Warnings

NOAA Technical Lead: Alan Gerard (NSSL)

NOAA Strategic Goal 2 – *Weather-Ready Nation – Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Task II

Objectives
The primary goals for this reporting period were to develop algorithms to detect storm scale features in radar and satellite data, and to use these features to issue probabilistic short-term predictions of severe weather events.

Accomplishments

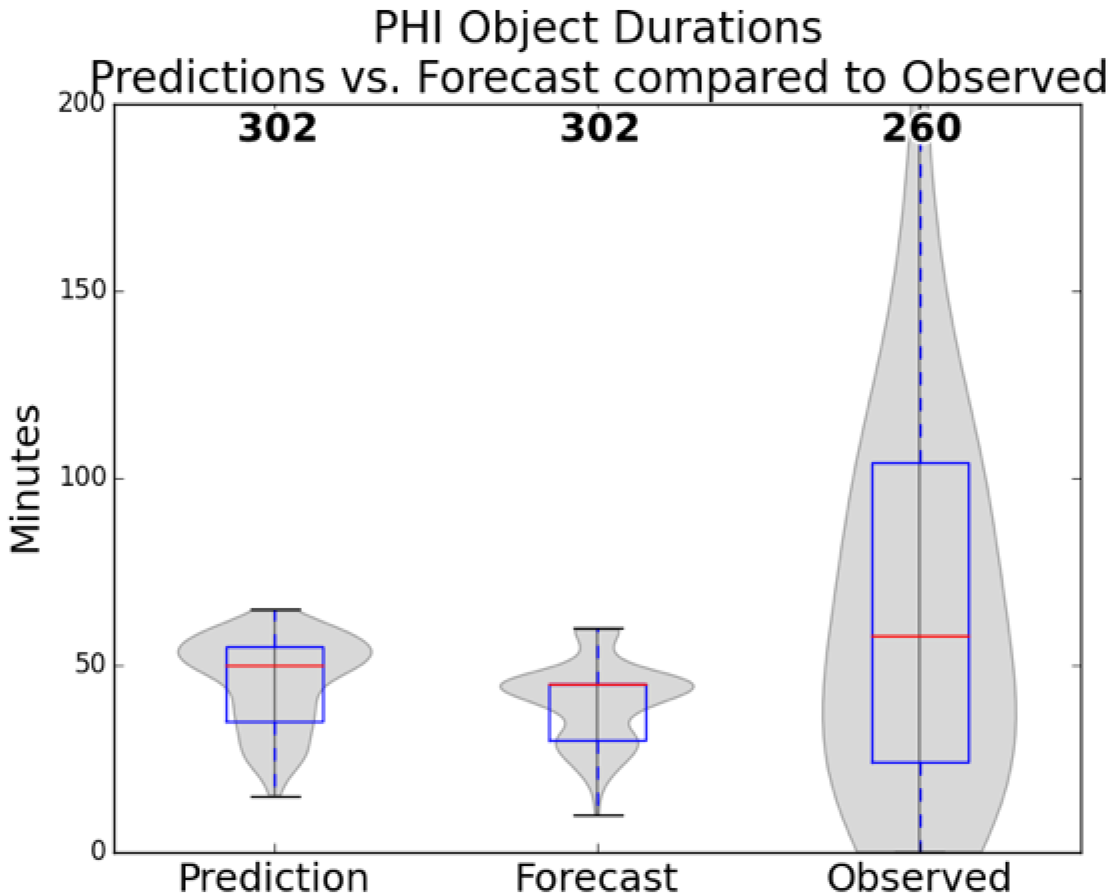
1. Machine Learning-Based Storm Classification and Duration Prediction

Chris Karstens and Travis Smith (CIMMS at NSSL), and Amy McGovern (OU Department of Computer Science)

During the evaluation period, two machine learning algorithms were developed and refined by Dr. Amy McGovern that predict 1) the duration and 2) the classification of severe convective storms identified as objects from the MRMS composite reflectivity. A real-time and displaced real-time feed of these objects were visualized and/or evaluated with forecasters in the Spring 2017 Probabilistic Hazard Information (PHI) experiment at the NOAA Hazardous Weather Testbed (HWT).

It was found the forecasters accepted and used the duration predictions in approximately 45% of the forecasts produced during the experiment, down from approximately 75% in the previous HWT. This result implies that forecasters have trust these predictions, or feel that the predictions are sufficient. However, evidence from prior experiments shows that forecasters rely heavily on default duration settings and local office policy (i.e., training).

Analyzing a set of forecaster issued durations compared to predictions and observations (figure below) suggest that the predictions provide a good first guess that can nudge forecasters toward better duration forecasts. Longer observed storm durations tend to be under-predicted, whereas shorter observed storm durations tend to be over-predicted. Thus, these limitations with the reliability spectrum should be emphasized to forecasters while urging them to consider discarding local office policy within a new warning paradigm.



The distribution of machine-based and human duration predictions for storm calls compared to observed storm curations.

2. Warn-on-Forecast

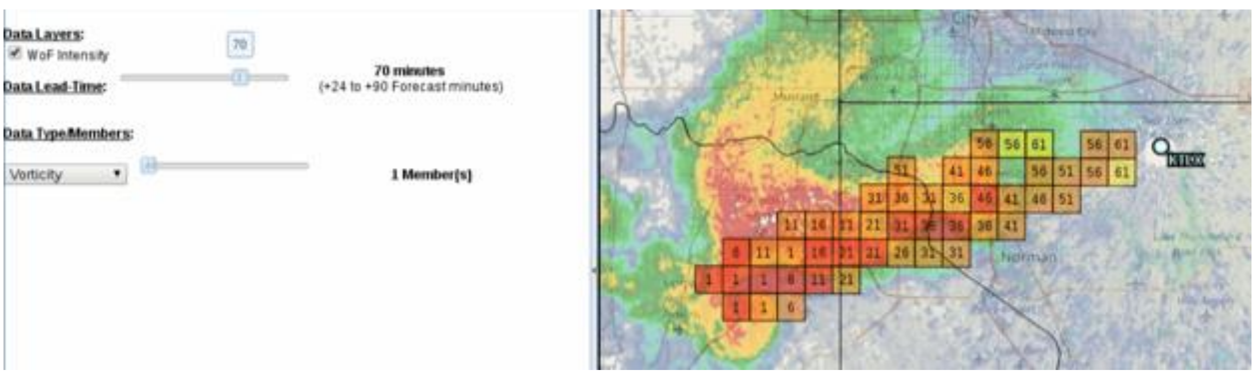
Chris Karstens (CIMMS at NSSL)

During the evaluation period, requests for automated quality-controlled radar datasets were facilitated. The source radars were primarily comprised of National Weather Service (NWS) WSR-88D radars, but also included terminal weather radars (e.g., TOKC) and research radars such as the Multiphase Phased Array Radar (MPAR) and experimental dual polarization radar (KOUN). These quality-controlled datasets were assimilated into analyses used to drive an ensemble of Numerical Weather Predication (NWP) models within the Warn-on-Forecast project.

Additionally, development, testing, and evaluation of probabilistic guidance from the NSSL experimental Warn-on-Forecast ensemble system (NEWS-e; figure below) was conducted during the Spring 2017 Probabilistic Hazard Information (PHI) experiment at the NOAA Hazardous Weather Testbed (HWT). This experiment utilizes a prototype web tool allowing forecasters to issue probabilistic forecasts for severe convective weather events (tornado, wind, hail, and lightning). The tool presented guidance

derived from object-based tracking of mid- and low-level vorticity. These grid points were overlaid on the spatial display, and could be filtered based on 1) ensemble member agreement 2) adjustable lead-time and 3) exceedance of an adjustable variable threshold. Forecasters used this information to guide the generation of probabilistic tornado forecasts for real-time and displaced real-time weather events.

Although this guidance is still in its preliminary stages of development, it was able to give forecasters more confidence while generating forecasts. In general, forecasters lack a source of guidance that provides explicit future prediction of severe convective weather events. Thus, the NEWS-e guidance was able to fill an information void for forecasters. This was evident when the guidance showed agreement on the prediction of mid- and/or low-level vorticity tracks, indicating a potential for tornadoes, and also when the guidance showed a lack of forecast tracks for a given storm at various forecast lead-times, indicating tornado demise or lack of sufficient rotation for the occurrence of tornadoes. Finally, the ability to adjust lead-times and variable thresholds on demand lead to improved understanding and trust of the guidance.



The forecaster interface to show probabilistic guidance from NEWS-e overlaid on radar reflectivity data.

3. Storm-Based Cloud-to-Ground Lightning Probabilities

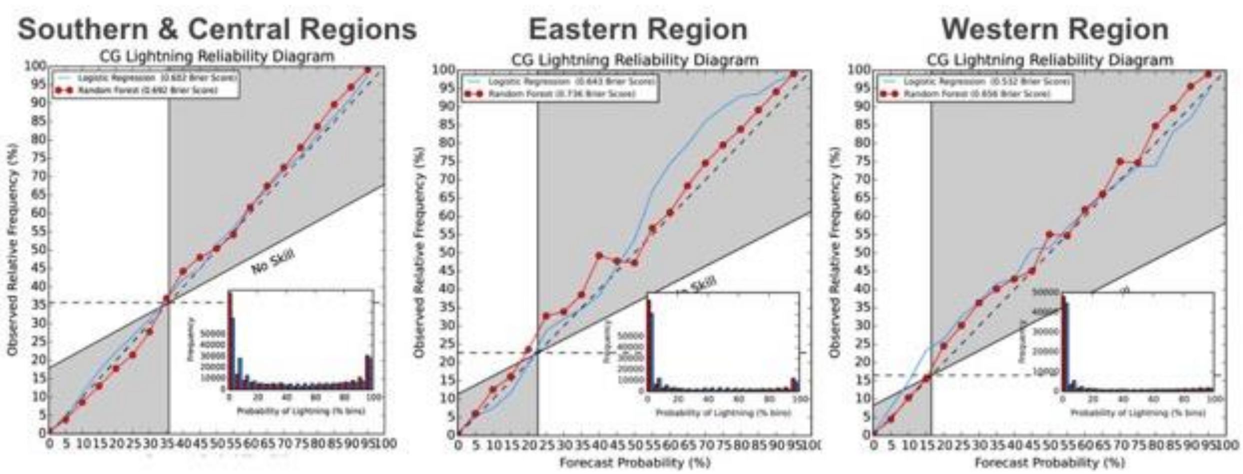
Kristin Calhoun, Tiffany Meyer, and Darrel Kingfield (CIMMS at NSSL)

A cloud-to-ground (CG) lightning probability algorithm has been developed using machine-learning methods. With storm-based inputs of Earth Networks' in-cloud lightning, Vaisala's CG lightning, multi-radar/multi-sensor (MRMS) radar derived products including the Maximum Expected Size of Hail (MESH) and Vertically Integrated Liquid (VIL), and near storm environmental data including lapse rate and CAPE, a random forest algorithm was trained to produce probabilities of CG lightning up to one-hour in advance. Recent advancements in the algorithm include: (1) tailoring the guidance by NWS region to address geographically-variable convective modes (first figure below), (2) expanding our training dataset to include 2015 (now includes > 1,506,000 total storm samples) and (3) creation of statistical guidance for the frequency of flash rates.

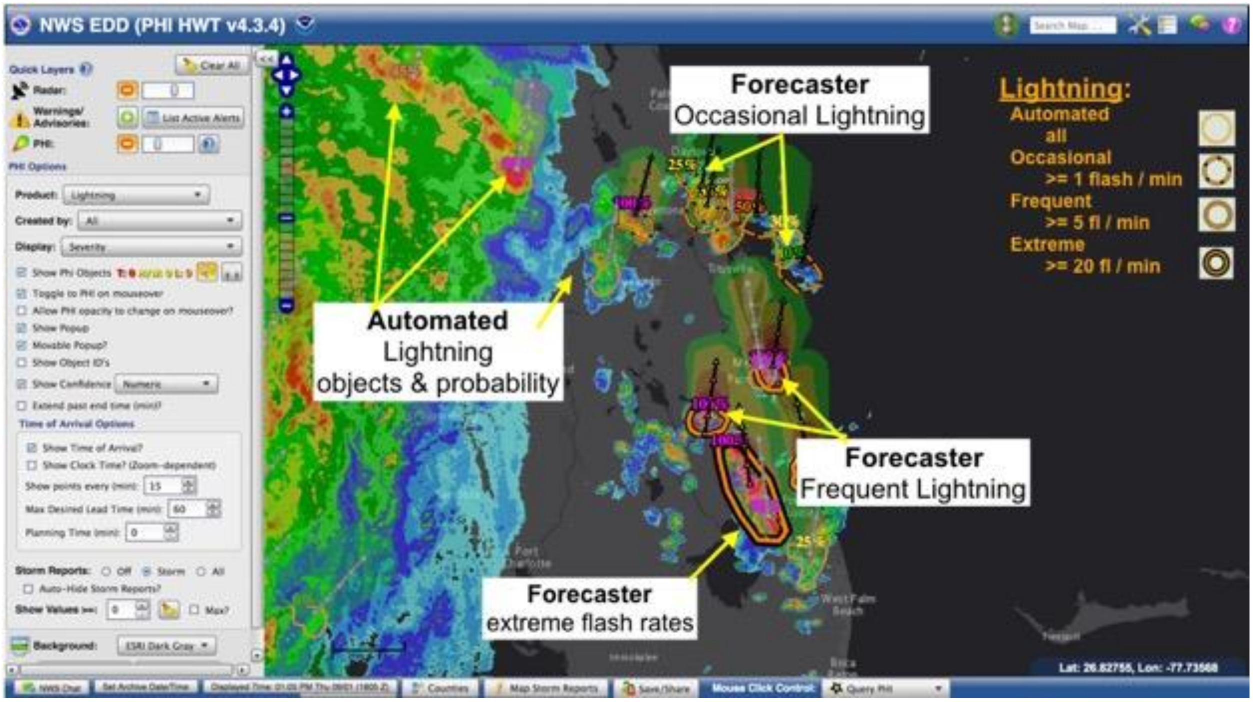
As part of the Probabilistic Hazard Information (PHI) Experiment in the Hazardous Weather Testbed (HWT), an integrated warning team of National Weather Service (NWS) forecasters, emergency managers, and broadcast meteorologists were asked to issue, utilize and evaluate probabilistic cloud-to-ground (CG) lightning hazards and warnings in context of their typical activities (second figure below). While lightning poses a significant hazard to lives and property, a lightning-specific product does not exist. The PHI tool was utilized in our experiment by NWS forecasters to communicate lightning hazards to end-users.

Forecasters participating in the experiments were receptive to the probabilistic CG lightning algorithms and guidance and greatly anticipated the use within Decision Support Services and for general communication of public safety. However, forecasters commonly noted a current lack of training and understanding in regards to various types of lightning data available and for forecasting CG lightning.

Feedback from emergency managers consistently revealed a high desire for access to this lightning hazard information within their daily operations. In addition to confirming an end-user need, testing revealed that effective communication of lightning objects was sometimes lacking and communication of lightning information in this format could be difficult. Additional research is underway to incorporate relevant social and behavioral science methodologies to communicate lightning threats such that end-users can successfully assess and understand the information and take appropriate action.



Reliability diagrams for the storm-based CG probability algorithm for the various NWS regions. Due to similarity of the datasets, Central and Southern Regions were grouped together whereas differences in Eastern and Western regions necessitated individual algorithm development for enhanced performance.



NWS Enhanced Data Display for CG lightning probability objects and local radar over Melbourne, FL from 1 Sept 2016. Objects are outlined by the storm area with the line denoted the current and/or forecast CG rates (see legend, top right). Probability can be displayed as either a number (as shown) or words (i.e., low, medium, high; not shown). Forecast tracks, forecaster discussion, and probability grid may also be displayed by end users (not shown).

4. Development and Testing of Divergent Shear Algorithm

Matt Mahalik, Brandon Smith, Holly Obermeier, Kim Elmore, and Travis Smith (CIMMS at NSSL)

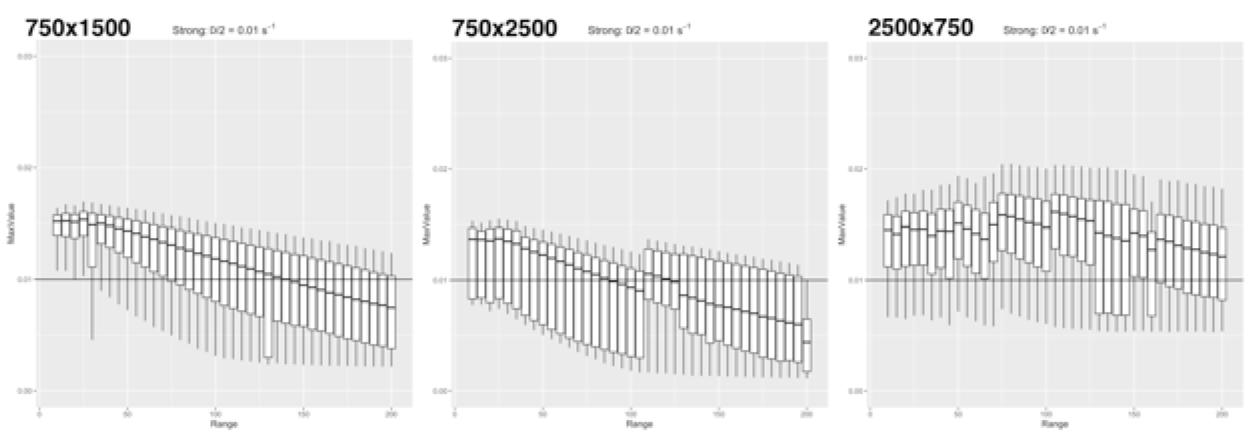
The algorithm used to generate azimuthal shear (AzShear) was recently re-worked and optimized, resulting in a complete and more mathematically sound set of local, linear, least-squares derivative (LLSD) equations for calculating 2D gradients in a radial data field. The same updated LLSD equations used for AzShear can also be solved for the along azimuth shear component, yielding an expression for 2D radial half-divergence (positive) and half-convergence (negative). The resulting product is referred to as LLSD divergent shear (DivShear). The new DivShear equations were implemented into the w2circ WDSS-II algorithm, which has the ability to calculate either LLSD shear component.

Like any LLSD quantity, DivShear is dependent on both range from radar and the size of the kernel over which the gradients are calculated. To determine a suitable kernel size for DivShear calculations of WSR-88D data, a numerical model was used to simulate a suite of divergent velocity signatures, each varying in (a) distance between velocity extrema (ranging from 250-8000 m), (b) magnitude of across feature delta-

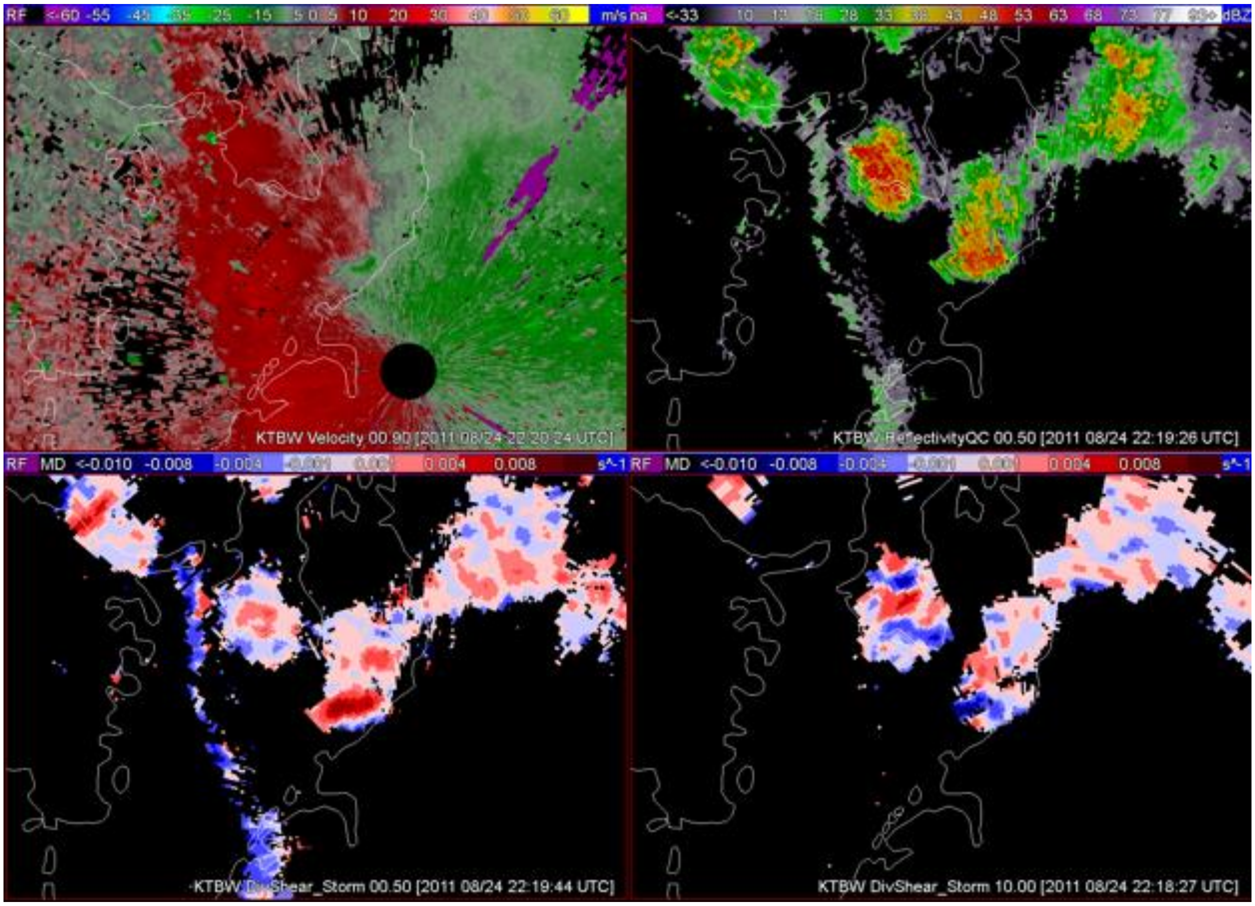
velocity (10-40 m s^{-1}), and (c) range from radar (10-200 km). Maximum DivShear values were calculated using several different kernel configurations for each simulation and were then compared to theoretical divergence (½ * dV/dR). The ability of LLSD to produce DivShear values consistent with theoretical divergence varied between kernel configurations and across the spectrum velocity signature attributes. Moderate and strong DivShear signatures were most consistently representative of "true" divergence when a kernel size of either 750 m x 1500 m or 750 m x 2500 m was implemented.

The first figure below summarizes range-based LLSD DivShear calculations for strong divergence signatures (defined as any signature whose width and delta-V produce a theoretical half-divergence of 0.01 s^{-1}) using three different kernel configurations. In general, LLSD DivShear underestimated small divergent features and overestimated weak and wide features regardless of kernel size. In addition, the ability to resolve small gradients decreased with range due to beamspreading, also a well-documented problem for the AzShear product. The slightly "deeper" kernel along the azimuth (2500 m deep) more often underestimated small features due to its larger horizontal footprint, thus producing a wider range DivShear output.

Initial, qualitative applications of DivShear have confirmed that many meteorological phenomena are associated with distinct divergence signatures. For example, the second figure below shows the radar presentation of a damaging downburst generated by an ordinary summer thunderstorm in a low-shear environment in Florida. A DivShear divergence maximum occurs in the low-level (0.5° elevation) scan while strong convergence (negative DivShear) is evident in the preceding 10° elevation scan. The convergent outflow/sea breeze hybrid boundary is also identifiable in low-level DivShear. The ability of DivShear to identify small-scale features within supercells, such as convergence zones, microbursts, and possibly strong circulations, also shows promise, and studies examining divergence signatures specific to severe convective storms, including tornadoes, will commence in the near future.



Distribution of maximum DivShear values calculated for three different LLSD kernel sizes (from left: 750 m wide x 1500 m deep, 750 m x 2500 m, and 2500 m x 750 m) across the same simulated divergent velocity signatures. The solid, horizontal line represents theoretical divergence.



Clockwise from top-left: 0.9° Dealiased velocity, 0.5° quality-controlled reflectivity, 10.0° mid-level LLSD DivShear, and 0.5° low-level LLSD DivShear for isolated, ordinary thunderstorms and nearby convergent boundary near Tampa, FL, from KTBW radar on 24 August 2011.

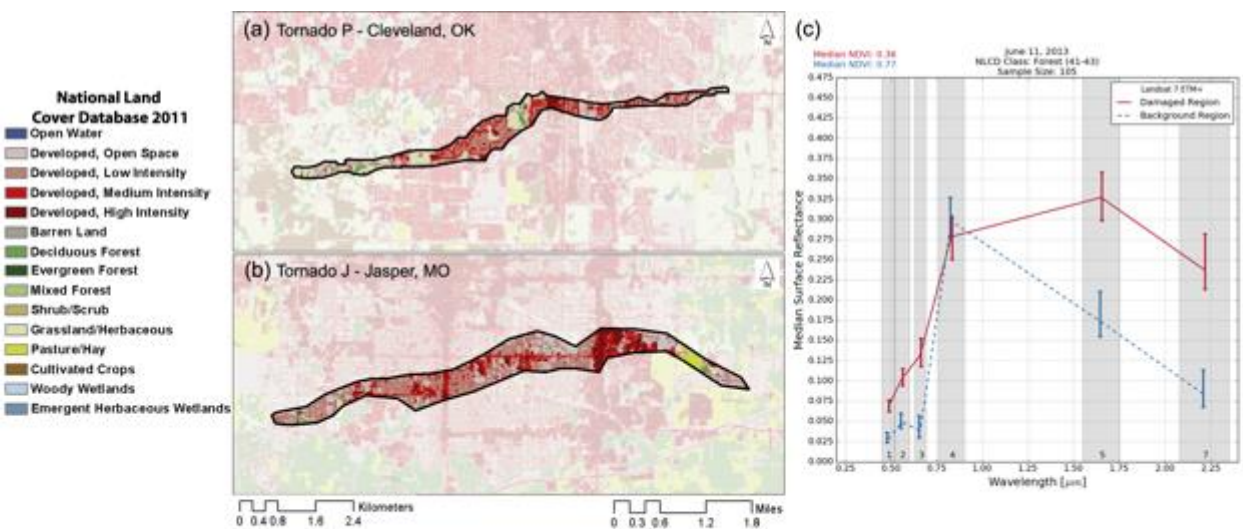
5. Landsat Satellite Identification of Tornado Damage

Darrel Kingfield (CIMMS at NSSL) and Kirsten de Beurs (OU Department of Geography and Environmental Sustainability)

Multispectral satellite imagery can provide a spaceborne perspective on the extent of tornado damage among other thunderstorm hazards at wavelengths beyond the limits of human vision. Yet, few studies have quantified how satellite-derived reflectance values change over different land cover types. Surface reflectance values from the Landsat 5 Thematic Mapper and Landsat 7 Enhanced Thematic Mapper Plus sensors were used to examine how 17 tornadoes modify grassland, forest, and urban land cover. These reflectance values were also combined to create Tasseled Cap brightness, greenness, and wetness fields along with a Normalized Difference Vegetation Index (NDVI) parameter for evaluation.

Most tornado damaged surfaces independent of land cover type measured a higher surface reflectance in the visible and shortwave infrared wavelength regions and a lower surface reflectance in the near-infrared wavelength region. These changes correspond to a higher tasseled cap brightness and lower tasseled cap greenness, wetness, and NDVI compared to undamaged areas. The magnitude of change was highest for tornado damaged forests where defoliation and broken/swept away trees fractured the closed canopy areas and revealed the bare ground below; fundamentally altering the surface reflectance profile.

Given that tornado damaged forests exhibit a similar spectral behavior as forest clearing, NDVI was compared to a disturbance index (DI) derived from the Tasseled Cap parameters to examine how each parameter performs in identifying forest damage and tracking its recovery. This was accomplished by examining five years of Landsat data (2009-2014) surrounding to 27 April 2011 tornado outbreak. NDVI, a commonly-used metric to identify tornado damage, and DI both were able to initially identify the locations of tornado damage, however, NDVI varies from image-to-image due to the cyclical vegetation cycle (highest NDVI in the spring/summer, lowest in the fall/winter). This make a time-series assessment of damage recovery using NDVI quite difficult. Alternatively, DI remained nearly stable across the two years of images prior to the tornado outbreak, peaked to its highest values up to six months after the tornado outbreak, and declined back towards pre-outbreak values coincident with recovery. This makes the DI and other indices derived like it a valuable gap-filling tool in identifying tornado damage in sparse vegetated areas that are difficult to reach by ground survey teams.



Tornado damage contour maps affecting (a) Cleveland County Oklahoma on 20 May 2013 and (b) Jasper County Missouri on 22 May 2011. The (c) spectral profile of damaged (red line) and undamaged (blue line) forests reveals a large amount of urban debris was thrown into the surrounding forested areas, dramatically increasing the surface reflectance in the visible (1-3) and shortwave infrared bands (5,7).

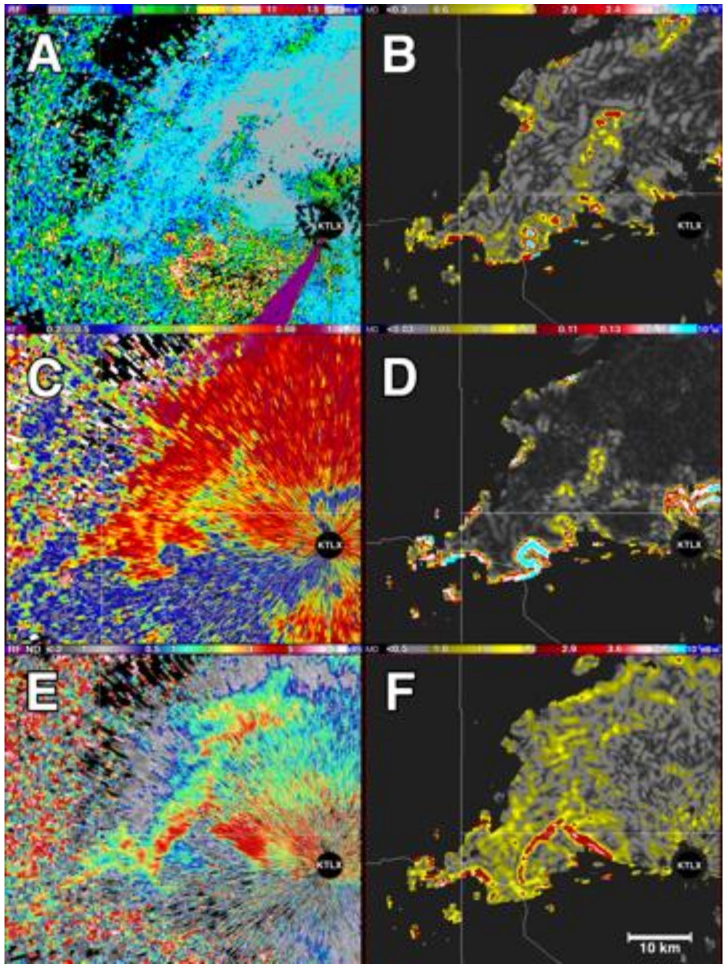
6. New Tornado Detection Algorithm

Kim Elmore, Matt Mahalik, Brandon Smith, and Don Burgess (CIMMS at NSSL)

The New Tornado Detection Algorithm (NTDA) prototype is being developed as a replacement for the current Tornado Detection Algorithm (TDA; Mitchell et al. 1998). Unlike previous iterations of the algorithm, the NTDA will employ a random forest machine learning technique that will evaluate a variety of radar and environment-based predictors. This approach automatically selects the predictors most useful for indicating the presence of a tornado, removing the need for a “model selection” step. The resulting classification process is streamlined and amenable to very efficient parallel processing.

Initial development required (1) a list of potential predictors, consisting of a wide range of real-time variables, including both radar-derived and environmental quantities, and (2) establishment of the means to produce the predictor fields. Two of the primary products selected for use are divergent shear (DivShear) and azimuthal shear (AzShear) velocity gradients, which are calculated using local, linear, least-squares derivatives (LLSD). This method of gradient calculation was expanded to produce gradients of non-velocity radar fields including those of reflectivity and polarimetric variables, which often provide additional information about small-scale processes occurring within a storm. For scalar variables, additional code was written to compute a “total” LLSD gradient--a combined azimuthal and radial gradient--by calculating the norm of the two LLSD gradient components. The proposed NTDA random forest will be fed these LLSD output predictors--including AzShear, DivShear, and total LLSD gradients of spectrum width, cross-correlation coefficient (ρ_{hv}), and differential reflectivity (Z_{DR})--in conjunction with Rapid Refresh environmental data (such as CAPE, CIN, STP, and others) to identify features whose characteristics most closely resemble those of confirmed tornadoes.

The structure of the NTDA prototype is currently under development. Initial work has developed algorithms to calculate various LLSD field outputs for Level II WSR-88D radar data associated with storms from a multi-year dataset of supercells, as identified by the Storm Prediction Center (SPC). These data will be used for testing and training the NTDA. Once initial development of the NTDA random forest is complete, scoring will be done for an independent test data set. This provides insight into how well the algorithm generalizes on data similar to, but independent of the training data.



Spectrum width (a), ρ_{hv} (c), and Z_{DR} (e) of a tornadic supercell near Moore, OK, from a KTLX 0.5° elevation scan on 20 May 2013, and corresponding 0.5° LLSD gradients of each (b, d, and f, respectively). All LLSD gradients are thresholded by 20+ dBZ 0.5° QC reflectivity.

7. New Mesocyclone Detection Algorithm

Matt Mahalik and Brandon Smith (CIMMS at NSSL)

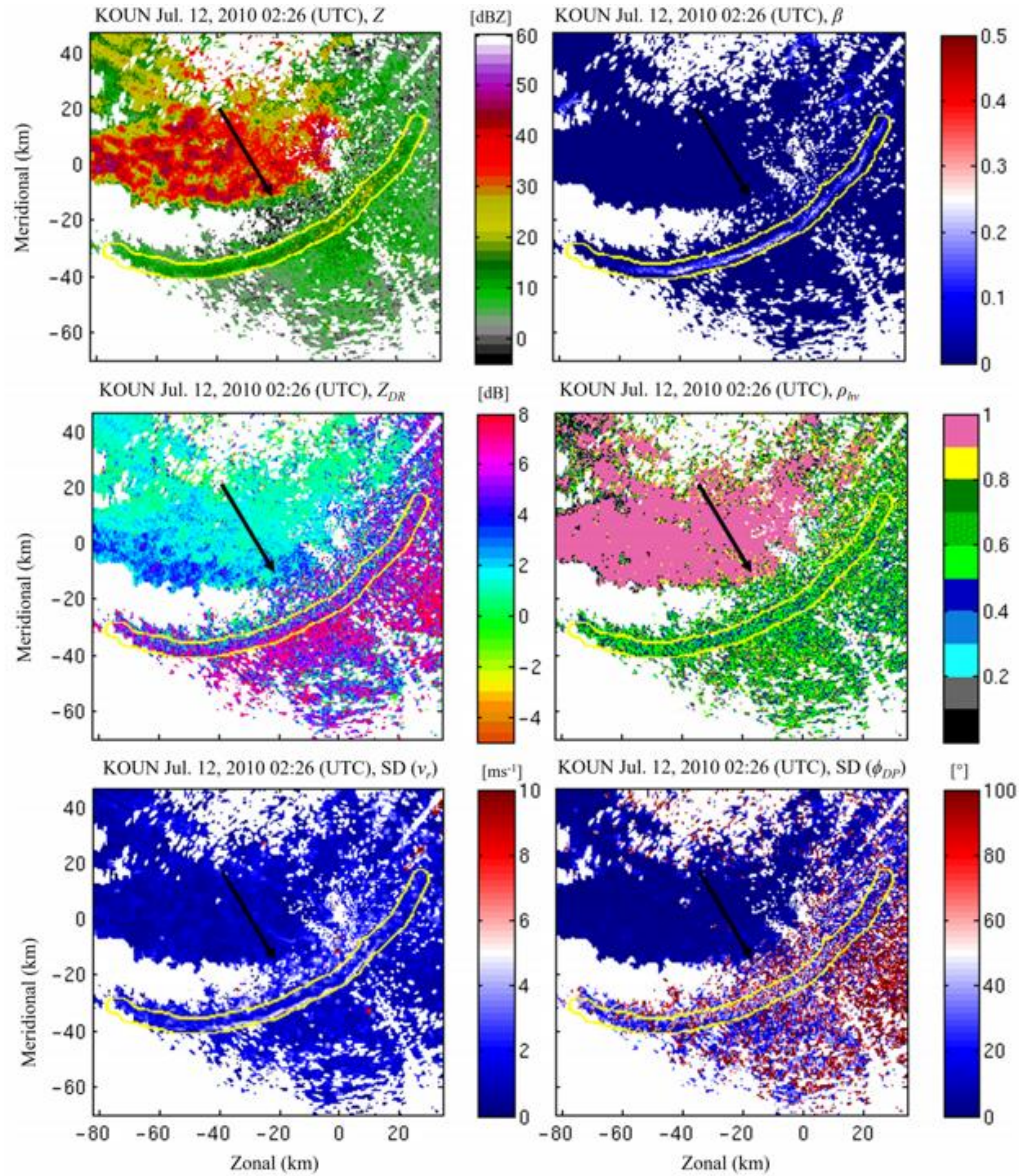
The New Mesocyclone Detection Algorithm (NMDA) prototype is being developed as a replacement for the current Mesocyclone Detection Algorithm (MDA; Stumpf et al. 1998) for the WSR-88D system. Unlike the MDA, the NMDA will utilize velocity derived outputs from the improved local, linear, least-squares derivative (LLSD) based azimuthal shear (AzShear) algorithm to produce detections of mesocyclones. These outputs that will aid in the detections include rotational velocity strength, change in velocity (delta-v), and shear diameter. Mesocyclone tracking and trending products are also being developed and will take advantage of the benefits provided by the newly implemented Multiple Elevation Scan Option Supplemental Adaptive Intra-Volume Low-Level Scan (MESO-SAILS) within the WSR-88D system.

8. Development of a Neuro-Fuzzy Gust Front Detection Algorithm

Darrel Kingfield (CIMMS at NSSL), Tian-You Yu (ARRC), Valliappa Lakshmanan (Google Inc.), and Yunsung Hwang, Dong-In Lee, and Cheol-Hwan You (Pukyong National University)

Rapidly descending air from a thunderstorm can spread out when it reaches the Earth's surface, creating a gust front that extends beyond the leading edge of a thunderstorm. Due to its displacement from the thunderstorm core, gust fronts may not be the immediate focus for decision support services but can be hazardous to aircraft operations and outdoor venues if not tracked accordingly. Leveraging the additional information from the polarimetric radar upgrade, a neuro-fuzzy gust front detection algorithm (NFGDA) was developed using a fuzzy logic interface system and optimized through the use of a neural network.

The NFGDA was evaluated against the currently operational machine intelligent gust front detection algorithm (MIGFA), built with single polarization radar fields, for 11 thunderstorm cases encompassing a total of 121 single-radar volume scans. Overall, NFGDA can provide a higher probability of detection/lower false alarm ratio (92%/0%) compared to MIGFA (78%/9%). Examining automated methods to estimate gust front length reveals NFGDA (MIGFA) can correctly estimate the total length of a gust front in 62% (41%) of cases and minimize false detected length to 7% (61%).



Radar parameter inputs into the neuro-fuzzy gust front detection algorithm around a gust front (yellow polygon) detected on 12 July 2010 at 02:26 UTC from the KOUN radar: (top left) reflectivity, (top right) line feature parameter, (middle left) differential reflectivity, (middle-right) copular cross-correlation coefficient, (bottom left) standard deviation of radial velocity, (bottom right) standard deviation of differential phase.

Publications

Hwang, Y., T-Y Yu, V. Lakshmanan, D. M. Kingfield, D-I Lee, and C-H You, 2017: Neuro-Fuzzy Gust Front Detection Algorithm With S-Band Polarimetric Radar. *IEEE Transactions on Geoscience and Remote Sensing*, **55**, 1618-1628.

Kingfield, D. M. and K. M. de Beurs, 2017: Landsat identification of tornado damage by land cover and an evaluation of damage recovery in forests. *Journal of Applied Meteorology and Climatology*, **56**, 965-987.

McGovern, A., K. L. Elmore, D. J. Gagne, II, S. E. Haupt, C. D. Karstens, R. Lagerquist, T. M. Smith, and J. K. Williams, 2017: Using artificial intelligence to improve real-time decision making for high-impact weather. *Bulletin of the American Meteorological Society,* Early Online Release. https://doi.org/10.1175/BAMS-D-16-0123.1.

Awards

Bulletin of the American Meteorological Society "Paper of Note" Recognition for the following paper, published in the June 2017 issue:

Kingfield, D.M. and K.M. de Beurs, 2017: Landsat identification of tornado damage by land cover and an evaluation of damage recovery in forests. *Journal of Applied Meteorology and Climatology*, **56**, 965-987.

ROC Project 10 – Analysis of Dual Polarized Weather Radar Observations of Severe Convective Storms to Understand Severe Storm Processes and Improve Warning Decision Support

NOAA Technical Leads: David McDonald and Terry Clark (ROC)

NOAA Strategic Goal 2 – *Weather-Ready Nation – Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Task II

Objectives (Projects 1 and 2)

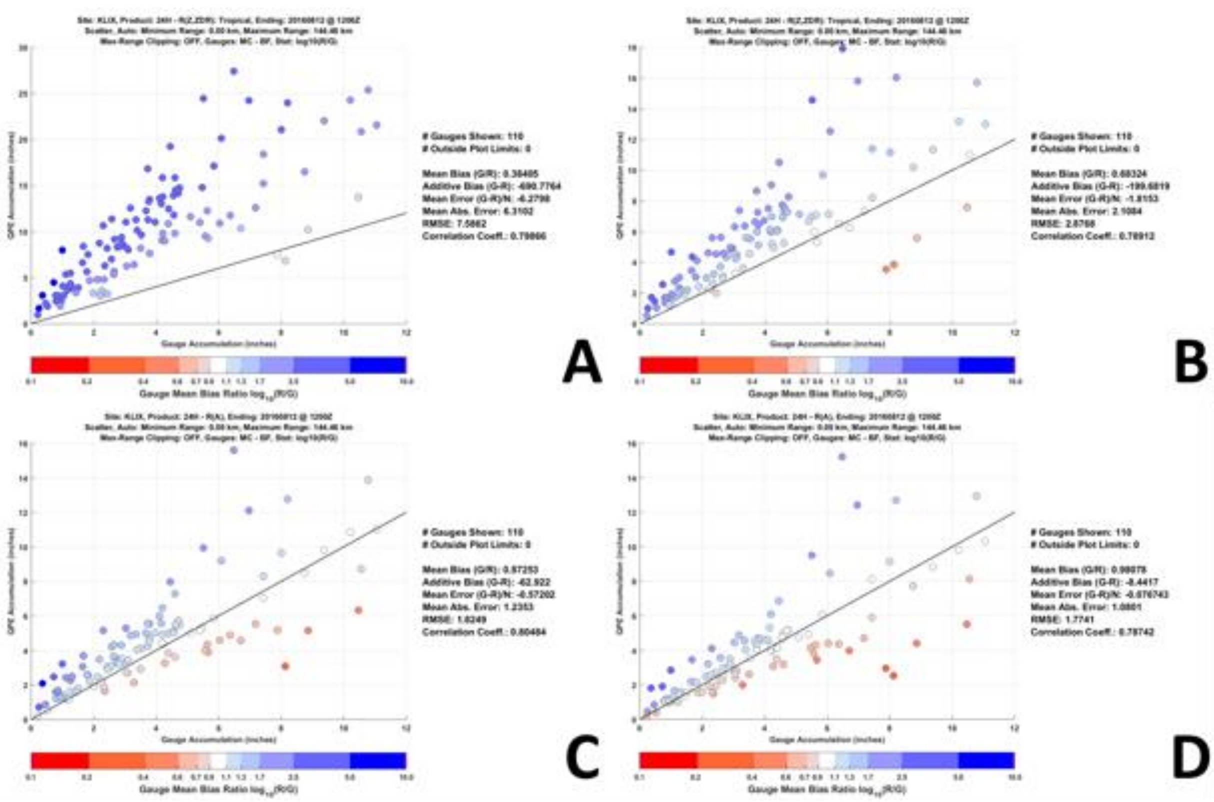
Evaluate the performance of changes implemented in the Radar Product Generator (RPG) software that involve applying a differential reflectivity (Z_{DR}) bias correction factor, and changes involving the ROC's implementation of the specific attenuation (R(A)) algorithm. Examine the performance of each software modification individually, and combined, by comparing the resultant derived precipitation accumulations (a principal component of quantitative precipitation estimation – QPE) using the various methods with rain gauge data. To aid in doing these QPE vs. rain gauge comparisons, software tools that have been previously developed for this purpose must be continuously maintained and upgraded to support the evolving needs and requirements of the end-users and to improve computing efficiency and usability.

1. Differential Reflectivity Bias Adjustment and Specific Attenuation Comparisons

Stephen Castleberry and Nicholas Goldacker (CIMMS at ROC), Zachary Biggs (Centuria at ROC), and Daniel Berkowitz, Richard Murnan, and Robert Lee (ROC)

Accomplishments

To aid in mitigating negative impacts to QPE caused by dual polarimetric (DP) radar data incorrectly estimating rain fall accumulations that are periodically reported by the NWS field sites, experimental techniques are being implemented in the RPG software in an attempt to resolve these issues. The two primary methods currently being tested include: applying a correction factor to the DP Z_{DR} data, called a bias adjustment in units of dB, and implementing a method of computing the rainfall rate using specific attenuation called R(A), where A is the specific attenuation in units of dB km^{-1}. In each case, the rainfall rate R in units of mm hr^{-1} depends on Z_{DR}, and thus each technique aims to improve the rainfall estimates, in part, by applying a correction to the Z_{DR} data. In addition to applying each technique individually, work is also being done to evaluate how they perform in tandem with one another. To evaluate the different RPG code modifications, approximately 18 test cases were selected from a variety of radar sites at different times of the year. Each case was processed using four separate RPG software configurations: an unmodified (baseline) playback, a playback with the Z_{DR} bias adjustment in place, a playback with R(A) in place, and a playback with both modifications in place. Afterwards, the results of each playback were individually analyzed with post-processing software (discussed in sub-project 2) that compares each playback's QPE accumulations with corresponding rain gauge data. The results of the QPE-rain gauge analyses were then compared with one another to determine which RPG software modification had the most desirable effect on the QPE data for each test case. The outcomes of one of the test cases are summarized in the figure below.



Scatterplots of radar-derived 24-hour QPE rainfall accumulations (in inches) vs. rain gauge accumulations (in inches) for the KLIX WSR-88D field site (located in Slidell, LA, near New Orleans) on the date of 08/12/2016 at 1200 UTC. For reference, this test case was selected during the record-setting rainfall and flooding event that occurred along the Gulf Coast in August 2016. Panel A shows the results of the baseline (unmodified) RPG software playback, panel B shows the results of the playback with the Z_{DR} bias adjustment applied, panel C shows the results of the playback with the R(A) (specific attenuation) modification in place, and panel D shows the results of the playback with both Z_{DR} bias adjustment and R(A) applied. In all cases, the QPE-gauge analyses were limited to below the base of the melting layer, which was calculated to occur approximately 144.46 km in range away from the radar at the time of this analysis. Additionally, each case used the exact same rain gauge data set consisting of both MRMS and CoCoRaHS gauge files, and the comparisons were colored using the scale shown which is derived from the mean bias ratio calculated using $log_{10}(R/G)$, where R is the radar QPE accumulation value and G is the rain gauge accumulation value. Judging from the scatter points shown, it can be seen that the unmodified RPG software exhibited substantial overestimates for this example. As corrections were applied, the scatter points tended to migrate closer and closer to the "ideal zone" in the diagrams around the solid reference line; points that fall along or near this line exhibit QPE-gauge pairs that had accumulation values very close to one another. Furthermore, looking at the reference statistical calculations, it is noticeable that the Z_{DR} adjustment and R(A) modifications applied individually each substantially improved the QPE-gauge results via increasing the mean bias (which ideally is as close to one (1) as possible), reducing the mean absolute error and root-mean-squared error, and moving the additive bias and mean error values closer to zero (0). The correlation coefficient did not vary substantially between each case. Comparing the results shown in panel D to the others, however, it is evident that the application of both the R(A) and Z_{DR} bias adjustment modifications in the RPG software was the most effective technique for reducing the radar-derived QPE overestimates seen in panel A using the baseline software.

2. Quantitative Precipitation Estimation Analyses Tool Upgrades and Documentation

Stephen Castleberry (CIMMS at ROC), and Heather Grams and Daniel Berkowitz (ROC)

Accomplishments

In order to facilitate the testing of RPG software changes that affect the way in which DP radar data are used to estimate precipitation rates and accumulations, continuous upgrades and improvements are required for the post-processing analysis software to ensure QPE-rain gauge comparison analyses continue to be performed correctly. Additionally, changes also must be periodically made to enhance functionality for the end-users and to ensure the software continues to meet the users' needs, as they evolve. The primary software that has been used extensively in the ROC Applications Branch for performing the QPE-gauge analyses is a complex system of Matlab scripts and a graphical user interface (GUI) that was previously developed by ROC and NSSL

personnel. Since its inception in early 2015, this software package has undergone extensive modifications and upgrades that include, but are not limited to: increasing computing efficiency, including more (and more useful) information on the plots and in the output text files, adding support for different rainfall rate calculation schemes (e.g. $R(Z, Z_{DR})$ and $R(A)$), adding compatibility for differently formatted rain gauge data files, allowing the user to queue multiple cases for processing at once, and increasing the usability of the GUI. Accordingly, as these changes are implemented, the documentation for this software is updated as well. The screen captures of the GUI shown in the figure below demonstrate some of the aforementioned changes that have been implemented to make the analysis software more user-friendly.

Sample Matlab GUI window both before (panel A) and after (panel B) the upgrades implemented in FY17. The GUI window provides a control panel for the user to select the input and configure the adaptable parameters for a given QPE-gauge analysis, in which text products, PPI plots, and scatterplots (such as those shown in Figure 1) are generated. The user can select the QPE data set, rain gauge data, save directory locations, data type and format, rainfall rate configuration, accumulation time interval, filtering and formatting parameters, and the date-time range for the analyses they wish to perform. Key functionality differences to note between the GUIs shown in panel A (pre-upgrade) and panel B (post-upgrade) include: a status panel (below the top row of options) that automatically detects the radar site ID and the number of QPE time samples available in the selected date-time range, green text indicating the current selections for the various check boxes and radio buttons to make it easier for the user to quickly verify which options they have selected, selection status indicators for the three check boxes in the "Formatting / Accumulation Parameters" panel that illuminate in green when their corresponding check box is activated, a field enabling the user to limit the analysis to a maximum range from the radar site, and an upgrade that changes the description text for the Min. Range Value, Max. Range Value, and Scatterplot Max Limit text boxes to active pushbuttons that can be used to quickly reset their respective text boxes to their default values in the event a mistake is made. These upgrades were implemented in response to feedback received from users in the ROC Applications Branch regarding usability issues and suggestions for improvements. Furthermore, the underlying analysis software that this GUI governs has also undergone substantial upgrades to enhance computing efficiency.

3. Analysis of Tornado Occurrence without a WSR-88D Signature on 9 May 2016

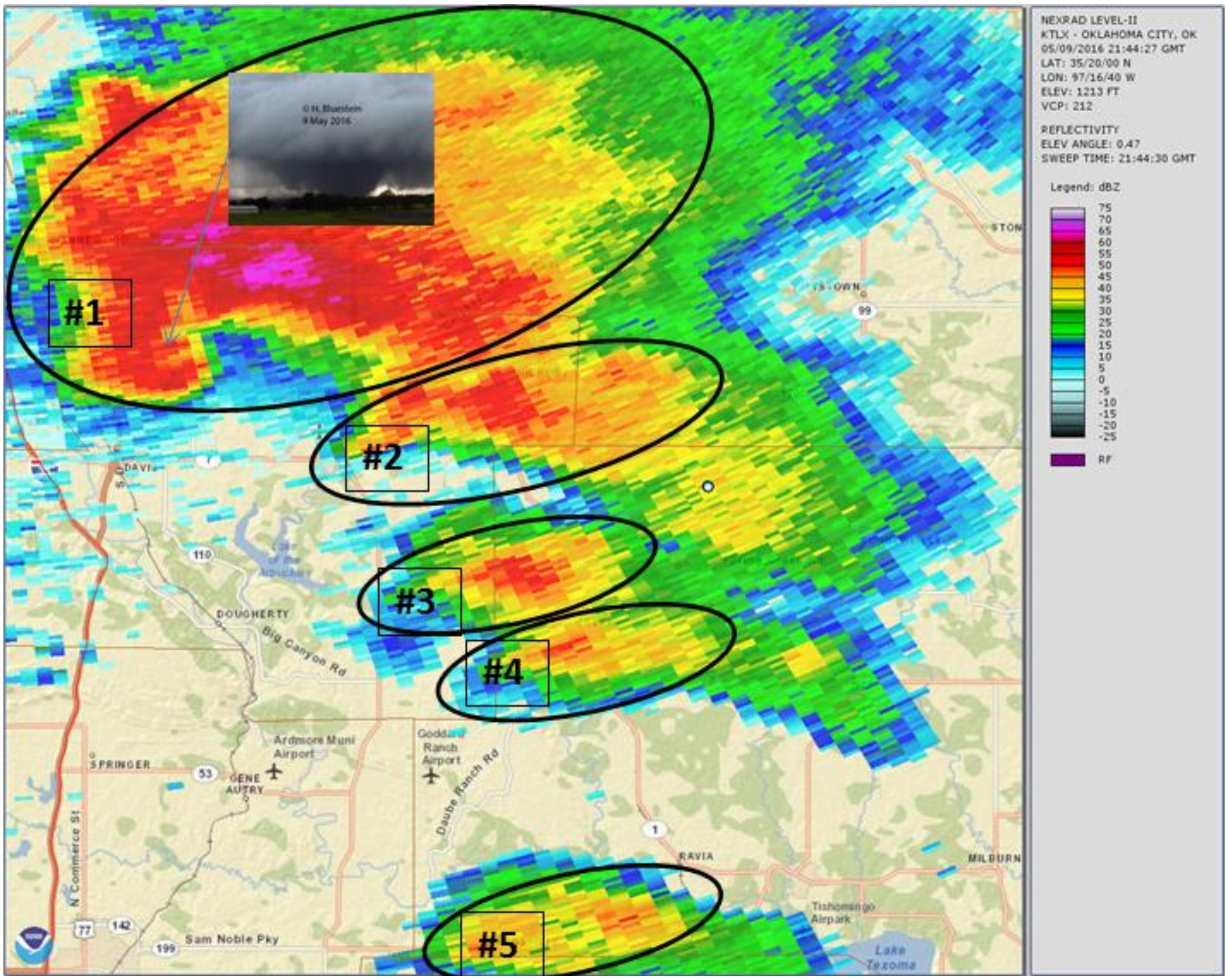
Don Burgess (CIMMS at ROC), Brandon Smith (CIMMS at NSSL), Howard Bluestein, Zach Wienhoff, and Dylan Reif (OU School of Meteorology), and Richard Smith and Doug Speheger (OUN)

Objectives
Analyze cases of difficult-to-detect WSR-88D severe weather signatures for documented severe weather events.

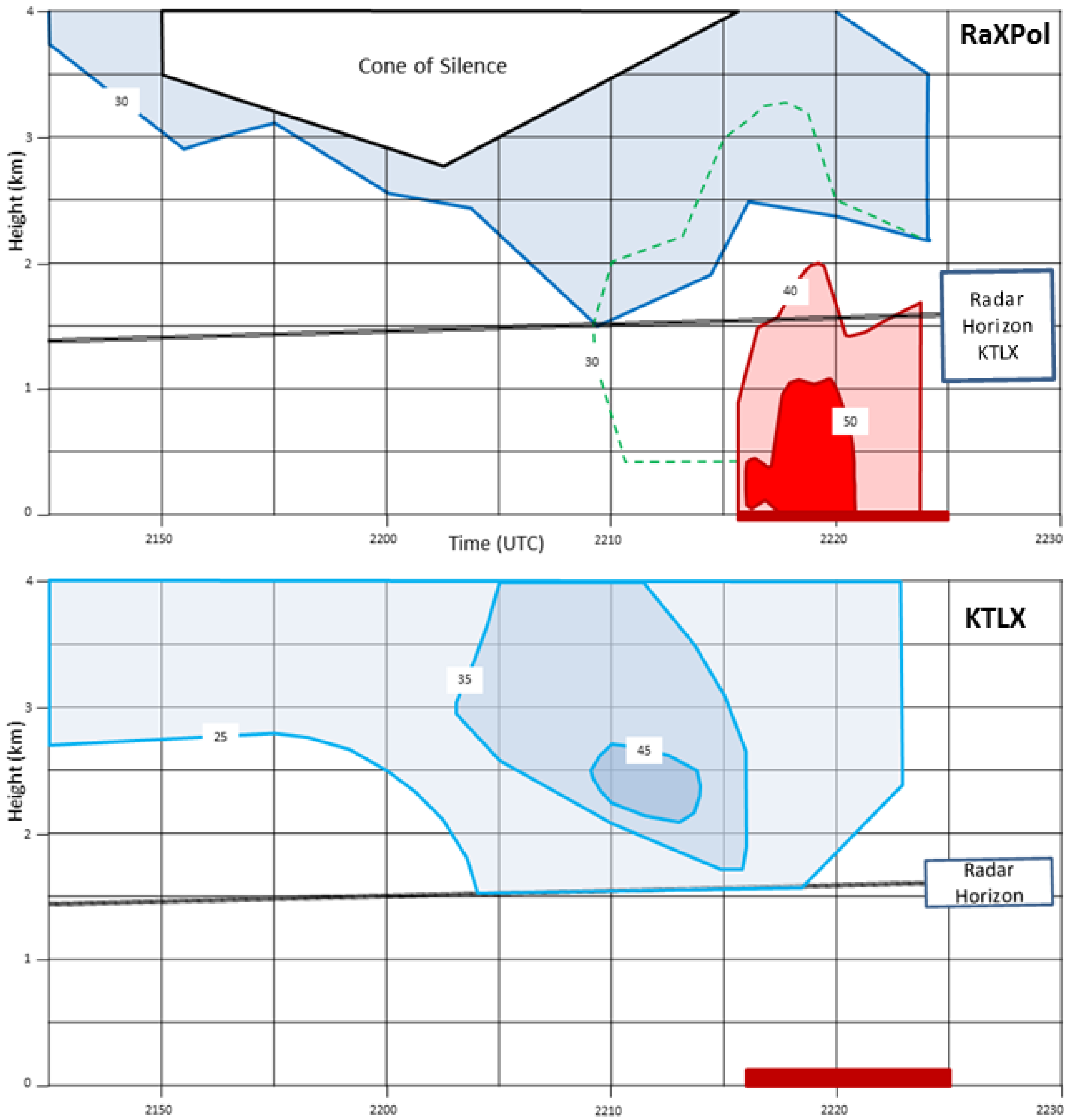
Accomplishments
On 9 May 2016, several supercell thunderstorms occurred in central and southern Oklahoma, resulting in a local outbreak of tornadoes and other severe convective weather. A small supercell developed amongst other small storms to the south of a large, strong, and tall supercell (LST Supercell). The LST Supercell produced strong and violent tornadoes (EF-4 and EF-3 the Enhanced Fujita Scale), while the small supercell, of a type sometimes called a Mini Supercell, produced a tornado that was in a very rural area and damaged only one barn (EF-0). The LST supercell (labelled #1) and the smaller storms, including the Mini Supercell (labelled #3), are shown in the first figure below. Television helicopter and ground photographers collected video of tornadoes from the LST and Mini Supercells in real time, and they were shown live on local and national stations and networks, with confusion about which tornado was located where. Early warnings were provided for the LST Supercell tornadoes, but no warning was provided for the Mini Supercell tornado although it had a lifetime of 9 minutes.

Fortunately, a University of Oklahoma mobile radar (RaXPol; 3-cm wavelength) was nearby the Mini supercell and recorded its evolution at ranges of 15-25 km. This allowed comparison to observations from the Oklahoma City-area WSR-88D (KTLX; 10 cm wavelength) at ranges of 100-110 km from the Mini Supercell. KTLX was operating in a scan mode that featured multiple low-level scans, but only single mid-level scans within a 6.5-minute scan period. Because of experimental fast-scanning, RaXPol collected low and mid-level scans every 30 seconds. RaXPol's better spatial resolution (based on range to the storm) and rapid scanning made it an ideal platform to capture the evolution of the Mini Supercell. Analysis of RaXPol and KTLX Mesocyclone and Tornadic Vortex Signatures (second figure below) revealed several reasons why KTLX data did not provide signatures that would allow for tornado warnings. 1) the Mini-Supercell signatures were small, and the closer range of RaXPol allowed for better spatial resolution and a radar horizon that was closer the ground where the TVS signature developed (lowest 1.5 km ARL); 2) the longer KTLX volume-scan time failed to capture the rapid evolution of the Mesocyclone and TVS signatures; and 3) toward the end of the tornado's lifetime as it became rope-like, the mesocyclone weakened and the remaining TVS signature became too small for either radar to detect well. Analysis of Dual-Polarization data (not shown) revealed a Tornado Debris Signature within the RaXPol data, but no evidence of a Tornado Debris Signature within KTLX data.

Lessons to be learned from this case are; 1) Mini-Supercells can occur in the same environment as more-threatening LST Supercells, and 2) WSR-88D radar users should be aware that in certain conditions, Mini-Supercell tornadoes at ranges as small as ~100 km can occur without detectable Radial-Velocity or Dual-Polarization radar signatures.



KTLX 0.5º reflectivity at 2144Z on 9 May 2016 for an area of southern Oklahoma. Storm #1 is the LST Supercell with an inset of the violent tornado in progress at scan time (tornado image courtesy of H. Bluestein). Storm #3 is the Mini Supercell. Reflectivity scale at right.



Height/Time analysis of Mesocyclone velocity difference (Delta-V; in m/s; blue color) and TVS velocity difference (Delta-V; in m/s; red color) for RaXPol (top) and KTLX (below). Cone of silence (no data) marked for RaXPol (top), and Radar Horizon (no data) marked for KTLX (top and bottom). Dark red bar at 0 Height shows the time period of the Mini-Supercell tornado.

WDTD Project 12 – Warning Decision-Making Research and Training

NOAA Technical Lead: Ed Mahoney (WDTD)

NOAA Strategic Goal 2 – *Weather-Ready Nation – Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Task II

Objectives

Increase expertise among NOAA/NWS personnel and their core partners on the integrated elements of the warning process. CIMMS scientists conduct applied research, develop and deliver training, and build applications to support the mission of meeting this goal. In doing so, we help NOAA/NWS warning forecasters and their core partners better serve the general public during warning operations and other hazardous weather events that require weather decision support services.

Accomplishments

1. Advanced Weather Interactive Processing System - II (AWIPS-2) Training

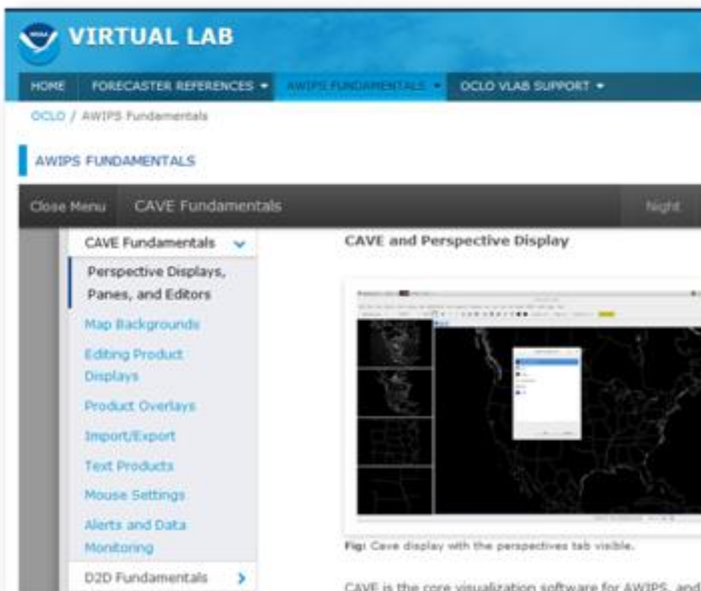
Eric Jacobsen, Dale Morris, Thao Pham, Stanislav Speransky, Phillip Ware, and Alex Zwink (CIMMS at WDTD)

NWS Weather Forecast Offices (WFOs) use the AWIPS-2 to analyze weather data and issue warning and forecast products to the public. CIMMS staff work with federal instructors at the Warning Decision Training Division (WDTD) to provide training for new NWS meteorologists and all forecasters as updated functionality is released via new AWIPS builds. During the past year, CIMMS staff contributed to AWIPS-2 training in three main areas. First, they participated in overhauling the AWIPS Fundamentals course to fit a new interactive website format. This training provides a baseline understanding of the AWIPS-2 system to new NWS employees. The AWIPS Fundamentals course uses a series of training videos, exercises, and job aids that incorporate the Weather Event Simulator - II (WES-2) Bridge to meet these training goals. Second, CIMMS staff created new AWIPS Informational Overview training modules to coincide with the AWIPS-2 software release schedule. These training offerings focus on the new enhancements and tools associated with each new software build. During the past year, these courses included training on AWIPS-2 Build 16.2.1, 16.2.2, 16.4.1, and 17.1.1. Lastly, CIMMS staff developed training on the AWIPS Interactive Reference (AIR) Contributor training. This tool provides a new direction for AWIPS instruction by providing forecasters easy access to reference material on their operational AWIPS-2 workstations.

In addition to supporting AWIPS training development, CIMMS staff at WDTD continually build extensive expertise on AWIPS-2 in order to support the technical needs of the WDTD's training mission. This expertise building includes maintaining

WDTD's real-time AWIPS-2 display system, developing comprehensive datasets for analysis, and assembling simulations for WDTD training projects. During this past year, AWIPS workstations used by CIMMS and NWS staff at WDTD were updated from AWIPS 14.3.1 to 16.4.1. Additionally, CIMMS staff created utility scripts for streamlining management of AWIPS data, operated in-house testbeds to compare new software and products against legacy tools, and collaborated with other federal agencies based on these testing results. The agencies collaborated with include the Radar Operations Center (ROC), National Severe Storms Laboratory (NSSL), the Hazardous Weather Testbed (HWT), the Global Systems Division (GSD), other NOAA partners, and the AWIPS contractor Raytheon.

This work is ongoing as AWIPS-2 has regular, frequent updates. CIMMS will continue providing a vital contribution to the testing, familiarization, and training delivery of AWIPS-II features to both the NWS Office of the Chief Learning Officer (NWS/OCLO) and the entire NWS organization.



Example from the AWIPS Fundamentals training, ported this year to an interactive web-based format via the NOAA/NWS Virtual Lab (VLab). VLab is a collaboration portal used across the NWS where CIMMS staff have contributed significantly and led the way in demonstrating its utility.

2. Fire Weather/IMET Training Distance Learning Skills Support

Alyssa Bates, Clark Payne, and Andrew Wood (CIMMS at WDTD)

NWS forecasters who participate in the Incident Meteorologist (IMET) program are required to complete safety and other related training on a regular basis. Previously, this recurring training was only available through in-residence courses or by forecasters reviewing the training material at their local office. This situation prevented NWS

headquarters personnel from rigorously monitoring training completions for all of these required courses.

To address this issue, CIMMS scientists worked as part of a team tasked with reformatting these IMET safety courses from in-person PowerPoint presentations to interactive, on-line modules. As part of this task, they reformatted four safety lessons for on-line delivery and made them available via the Commerce Learning Center (CLC). WDTD CIMMS then gave IMET training officers informal instructions on how to track a forecaster's progress with these courses in the CLC. This implementation received positive feedback from the IMET community as a whole.

Plans for future work have been discussed, such as making the existing courses more robust or reformatting other IMET training courses. However, unless these plans get funded in the future, this project is complete.

Interactive lesson navigation menu in the IMET Nautical Safety module.

3. Geostationary Operational Environmental Satellites (GOES) – R Infusion into WDTD Training

Dale Morris and Alex Zwink (CIMMS at WDTD), and Michael Bowlan (CIMMS at SPC)

With the launch of GOES-16 (and the future launch of GOES-S), CIMMS scientists helped prepare forecasters for all of the new data that will be available for WFO operations. In the past year, CIMMS invested a significant amount of time advising, developing, and supporting the Satellite Foundational Course for GOES-R (SatFC-G) in preparation for GOES-16 becoming operational. The Satellite Foundational Course

features a series of on-line modules developed through a partnership between the Cooperative Institute for Meteorological Satellite Studies (CIMSS), the COMET program, the Cooperative Institute for Research in the Atmosphere (CIRA), and the Short-term Prediction Research and Transition Center (SPoRT). To help forecasters apply the online learning, CIMMS scientists produced a set of 15 job sheets based on performance objectives to identify major meteorological features using currently available data as proxies for GOES-16 (such as GOES-14 Super Rapid Scan and Japanese Himawari-8 satellite data). These job sheets and case data were distributed to every weather forecast office (WFO) for use on their Weather Event Simulator – II (WES-2) Bridge workstations. The distribution of these cases presented a challenge due to the large amounts of data the satellites generate. The final package delivered to each office contained eight BluRay discs even after careful trimming of the datasets. However, these training exercises provide a crucial component in transferring the GOES-16 technology research results into practice for both forecasting and warning operations.

In addition to training designed for individual forecasters, CIMMS staff participated during the GOES-R Prep Course in Kansas City. These three-day courses prepared each Science and Operations Officers (SOOs) and Development and Operations Hydrologists (DOHs) to facilitate the foundational course for the staff at their local WFO. CIMMS staff created a six-workstation WES-2 Bridge laboratory at the National Weather Service Training Center and conducted lab sessions for each of the seven workshops to aid the course facilitators in learning key concepts. CIMMS personnel also collaborated with CIMSS to deploy their Satellite Information Familiarization Tool (SIFT) software as part of the GOES-R preparedness training. Both CIMSS and the Scientific Support Division Chiefs of each NWS regional headquarters office desired a functional SIFT at each WFO, but no platform capable of running this software existed at each NWS office other than the WES-2 Bridge workstation. CIMMS staff collaborated with each NWS region and the AWIPS program to identify the necessary software and hardware modifications and procure them for these workstations in a cost-effective manner that was acceptable to all. Additionally, CIMMS developed and distributed installation materials for the SIFT modification to each WFO along with data provided by CIMSS.

Following the satellite launch and subsequent distribution of live data, CIMMS staff monitored live data routinely for the prospect of updating other WDTD courses. CIMMS personnel archived these data on a case-by-case basis for possible use in lessons and accompanying training simulations distributed by WDTD. This work is ongoing and will continue as GOES-R research and analysis results become infused across all hazard training at WDTD.

CIMMS scientist Michael Bowlan leading a WES-2 Bridge lab session during the GOES-R Prep Course at the National Weather Service Training Center in Kansas City.

4. Multi-Radar/Multi-Sensor (MRMS) Training

Alyssa Bates, Jill Hardy, Eric Jacobsen, Clark Payne, Stanislav Speransky, Andrew Wood, and Brad Workman (CIMMS at WDTD), and Steve Martinaitis (CIMMS at NSSL)

NSSL developed MRMS products over the past decade to overcome limitations inherent in single-sensor products. Many of the MRMS products have been fielded for operational use across the NWS for over a year. CIMMS scientists have been heavily involved in the testing and training for this operational deployment of the MRMS system across the NWS.

WDTD created the initial training for MRMS products as part of the original release in 2014, and continue to maintain and update the available training. In September 2016, CIMMS staff released a suite of severe weather applications modules to aid forecasters with warning decision making. These lessons included applications on using MRMS products when nowcasting convection initiation, identifying convective mode, and detecting hail and tornado hazards. Several MRMS products lessons updates were also

released at that time as part of the MRMS Version 11 product upgrade. Lastly, two lessons detailing the new Flooded Locations And Simulated Hydrographs (FLASH) products were released in February 2017. Future work by CIMMS staff will focus on further product updates and MRMS applications outside the Continental U.S. (OCONUS).

In addition to training modules, CIMMS scientists maintain an in-depth reference guide of MRMS product descriptions in the NOAA/NWS Virtual Laboratory (VLab). NWS forecasters can access this reference guidance on their operational AWIPS-2 workstations, as needed, for “just-in-time” refresher information when using MRMS data during an event. This work is ongoing.

A slide in the Evaluation of Severe Hail Hazard module in the MRMS Applications Course Part 2.

5. Radar & Applications Course

Alyssa Bates, Jill Hardy, Austin Harris, Eric Jacobsen, Dale Morris, Stephen Mullens, Clark Payne, Matt Sienkiewicz, Chris Spannagle, Stanislav Speransky, Phillip Ware, Andy Wood, Brad Workman, Alex Zwink (CIMMS at WDTD), and Michael Bowlan (CIMMS at SPC)

The Radar & Applications Course (RAC) continues to be an area of active collaboration between CIMMS and the NWS Warning Decision Training Division. The RAC prepares new (and some veteran) NWS forecasters for warning operations by teaching a variety of topics related to the Weather Surveillance Radar – 1988 Doppler (WSR-88D). These topics include: radar theory, radar principles, radar data interpretation, storm interrogation techniques, and severe storm threat assessment and forecasting. All forecasters who may be responsible for issuing warnings in the future must complete

the course, as required by the NWS. Forecasters learn the material through a combination of teletraining, web-based instruction, on-station training, and in-residence training.

CIMMS staff members work extensively on the RAC, a course containing over 100 individual learning objects that take more than 75 hours to complete. This work requires collaborative work between CIMMS, WDTD federal instructors, Radar Operations Center engineers and software developers, and numerous other forecasters and scientists in order for successful training outcomes to occur. CIMMS scientists work on this project was varied. This work includes applied research on recent radar-related capabilities and applications to severe weather and flash flooding threats; creating training materials, exercises, and simulations; delivering presentations; and providing expertise on warning-decision making issues to the class participants.

CIMMS staff play a critical role during the in-residence component of RAC. CIMMS staff prepare, maintain, and update the Weather Event Simulator – II (WES-2) Bridge in the WDTD lab, which allows forecasters to simulate previous weather events using Advanced Weather Interactive Processing System – II (AWIPS-2) displays. Akin to flight simulations for pilots, this lab allows for collaborative simulations where groups of trainee forecasters share warning responsibilities while acting as a single WFO. In addition to keeping the WES-2 Bridge and AWIPS-2 workstations operationally representative, CIMMS staff works closely with WDTD instructors to develop and maintain the five full simulations, eight mini-scenarios, and two case exercises used during the workshop portion of the RAC.

NWS forecasters participate in one of four week-long severe weather warning workshops during the Radar & Applications Course held in Norman, OK.

6. Science & Operations Officer (SOO) Development Course Support

Jill Hardy, Eric Jacobsen, Dale Morris, Clark Payne, Thao Pham, Chris Spannagle, Stanislav Speransky, Phillip Ware, Andrew Wood, and Alex Zwink (CIMMS at WDTD), Kristin Calhoun, Steve Martinaitis, and Tiffany Meyer (CIMMS at NSSL), and Michael Bowlan and William Line (CIMMS at SPC)

The Science and Operations Officer (SOO) at a National Weather Service (NWS) Weather Forecast Office (WFO) serves as the training officer for that particular office. In this role, they oversee and facilitate the professional development of the staff at that office, as well as infuse new science into the operational workflow at the office. Prior to 2015, SOOs attended two separate courses to train them on both of these aspects of their position. The first course, called the COMET Mesoscale Analysis and Prediction (COMAP) course, focused on mesoscale science topics. The second course, taught by the WDTD, taught adult learning facilitation skills to SOOs and their counterparts at River Forecast Center offices (i.e., Developmental and Operational Hydrologists or DOHs).

In 2015, the NWS Office of the Chief Learning Officer (OCLO) decided to create a new course for SOOs that combined elements from both COMAP and the WDTD facilitation training. For the 2016 course (held in late Summer), CIMMS personnel played significant supporting roles based on their specific areas of expertise. They collected and prepared laboratory data cases for several sessions, including severe storm structure, Multi-Radar Multi-Sensor/Flood Locations And Simulated Hydrographs (MRMS/FLASH), and Geostationary Operational Environmental Satellites – R (GOES-R). As part of this effort, CIMMS staff prepared an updated Weather Event Simulator – II (WES-2 Bridge) software and associated laboratory environment for the seven lab sessions during the course. Additionally, CIMMS scientists gave presentations to the class on convective storm structure, MRMS/FLASH, GOES-R, the Commerce Learning Center (CLC) learning management system, gamification principles to enhance learning, simulation theory, and WES-2 Bridge use for building exercises and simulations.

Additionally, due to sessions discussing GOES-R and JPSS (Joint Polar Satellite System), CIMMS staff collaborated extensively with two additional cooperative institutes (the Cooperative Institute for Research in the Atmosphere and the Cooperative Institute for Meteorological Satellite Studies) to ensure the effectiveness their WES-2 Bridge laboratory sessions. This work is ongoing.

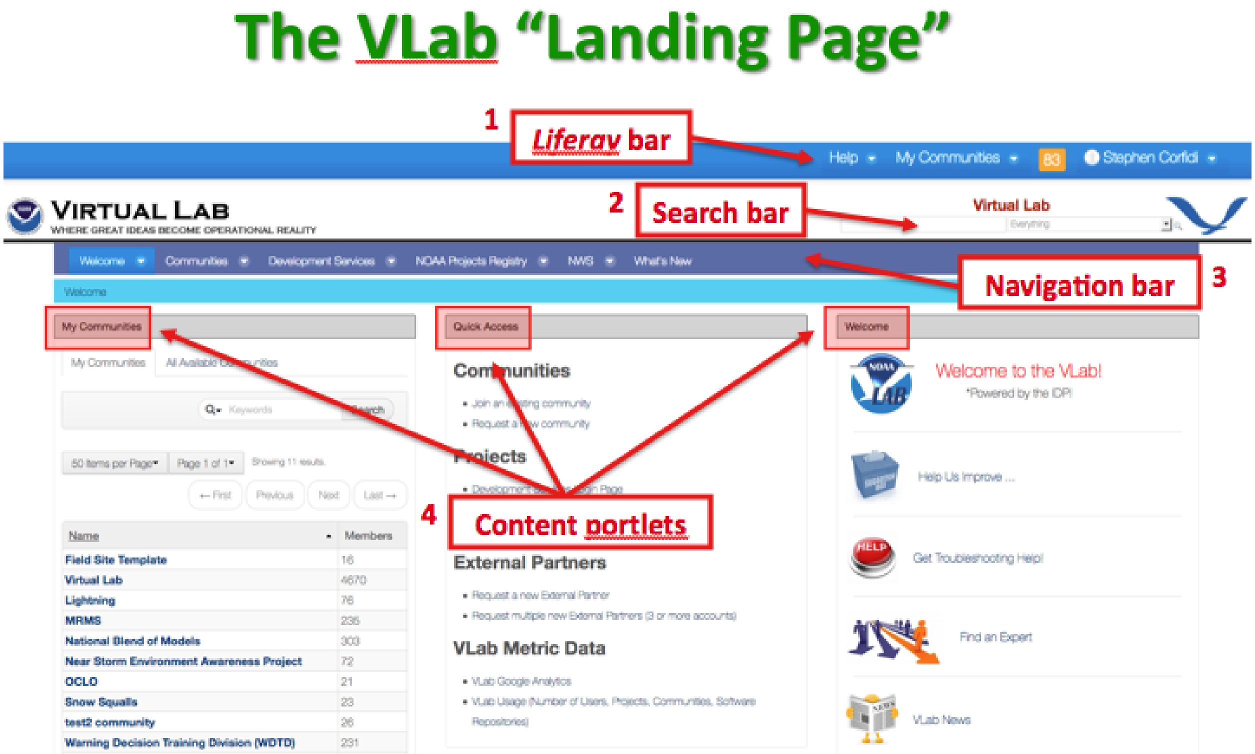
Convective Lab Session of the 2016 SOO Development Course. Each SOO used WES-2 Bridge to display new and experimental products in AWIPS in the context of a single Great Plains convective storm event. A CIMMS scientist discusses certain aspects of one-minute satellite data paired with radar data and additional experimental products in this event with a NWS SOO.

7. NOAA/NWS Virtual Laboratory (VLab) Training and Reference Support Implementation

Steven Corfidi, Eric Jacobsen, Thao Pham, and Stanislav Speransky (CIMMS at WDTD)

The NOAA/NWS Virtual Laboratory (VLab) provides a collaboration and development platform for NWS employees to share ideas, software, documentation, and other content. This system's ultimate goal is to improve NWS efficiency and reduce redundancy in areas of interoffice collaboration. CIMMS staff at the WDTD developed training on the VLab for use by other OCLO divisions and the SOO/DOH community to integrate VLab content into training and operations. An initial version of this training was given via webinars to staff at NWS national and regional headquarters in March 2017. The review process for the final training package remains in progress. The final training content discusses the need for VLab (including the need for training), an overview of the system's most fundamental tools and techniques, current applications of the system, potential uses for local training officers, and system limitations. This training should be available for NWS employees by the end of September 2017.

As part of this training effort, and to support other WDTD training initiatives, CIMMS staff have worked extensively to build expertise with the VLab. With this expertise, CIMMS staff trained other WDTD instructors how to use the VLab for their training needs. They also contributed to VLab theme and community redesigns, as well as best practices that apply for use by both the Office of the Chief Learning Officer (OCLO) and the NWS as a whole. Likewise, CIMMS staff have worked extensively with the AWIPS Interactive Reference (AIR) application that allows NWS forecasters to access VLab content directly from their AWIPS workstation. In fact, numerous references created by CIMMS staff and WDTD instructors were implemented in the VLab as part of the initial rollout of AIR to NWS Weather Forecast Offices (WFOs). Work on this project is ongoing.



Sample page from the "VLab Fundamentals" PowerPoint presentation being developed in preparation of the initial VLab training package.

8. Weather Event Simulator (WES) Development

Eric Jacobsen, Dale Morris, Thao Pham, Iqbal Virani, Philip Ware, and Alex Zwink (CIMMS at WDTD)

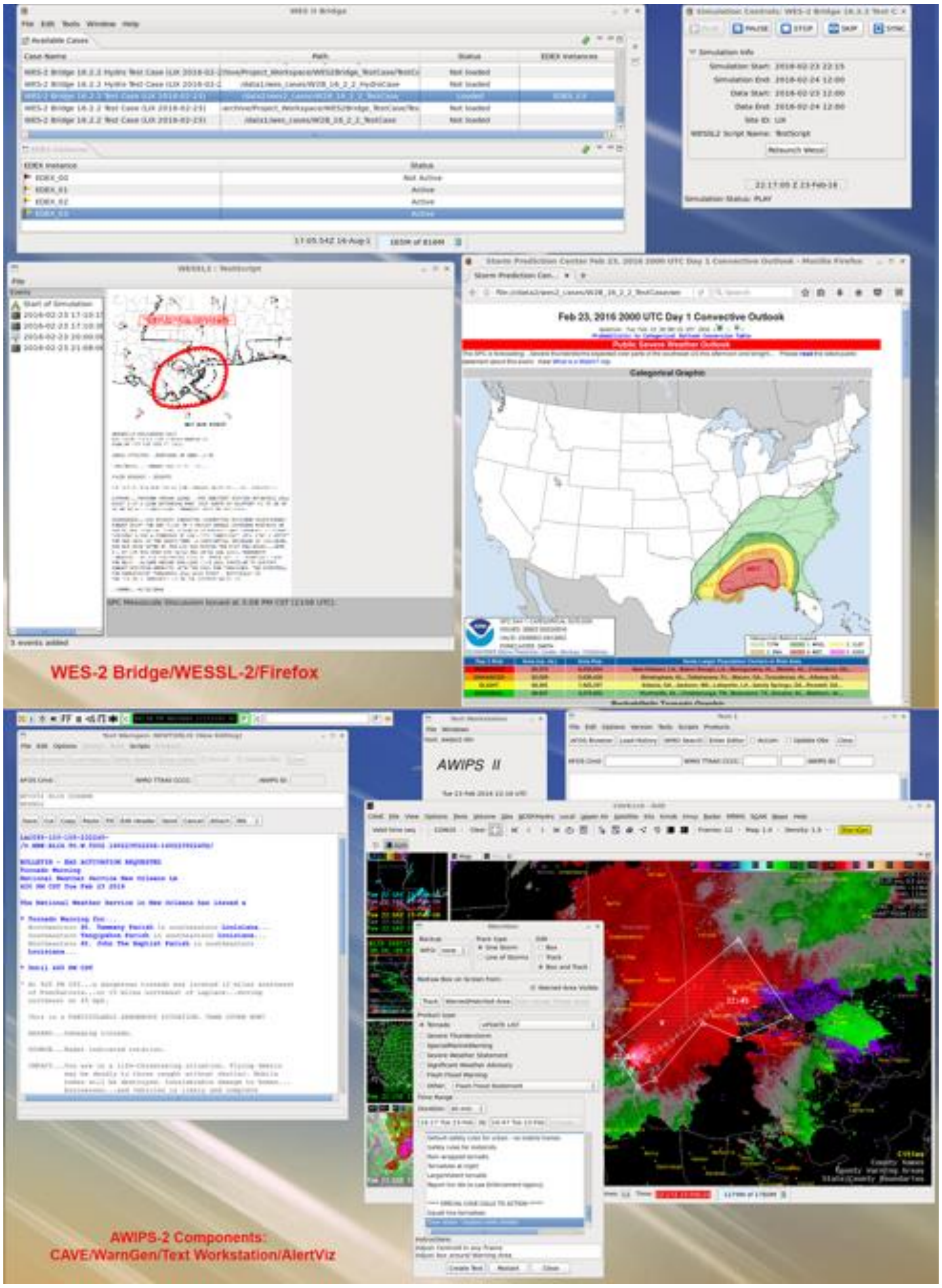
The Weather Event Simulator (WES) located in each NWS Weather Forecast Office (WFO) allows forecasters to meet the NWS Directive 20-101 requirement for every forecaster to complete two simulations prior to each significant weather season. CIMMS staff at WDTD developed the first generation WES over a decade ago because no such simulation capability was available within the operational AWIPS system. In order to

maintain this important capability with the upgrade to the Advanced Weather Interactive Processing Systems – II (AWIPS-2), CIMMS staff at WDTD developed a second generation simulator capability. The AWIPS program plans to add this simulator capability in the "baseline" system in the future. In the interim, the simulator developed by CIMMS staff serves as a "bridge" to that future solution. As a result, this AWIPS-2 simulator is called the WES-2 Bridge. The WES-2 Bridge allows forecasters to both simulate past weather events for training purposes, as well as view and analyze archived weather for local research projects. CIMMS personnel at WDTD serve a critical role as subject matter experts for the NWS AWIPS Program in regards to WES-2 Bridge. They work extensively to ensure compatibility between the WES-2 Bridge and new AWIPS build releases. The simulator represents significant engineering development because WES-2 Bridge has requirements above and beyond the normal AWIPS-2 system it emulates. The simulator features a tool (the WES Scripting Language or WESSL) for streamlined presentation of non-AWIPS information (such as spotter reports, video, briefings, web-based presentations, and engaging forecasters with feedback) during a simulation. Also, forecasters can use the WES-2 Bridge for both simulations with time-sequenced revelation of data (called displaced real-time or DRT) and case reviews where they can choose the time to view from a local WFO archive. Lastly, the simulator allows offices to reprocess raw data that they archive to ensure compatibility with future AWIPS-2 versions.

Significant work was conducted by CIMMS staff over the past year on the WES-2 Bridge. They upgraded the simulator to be compatible with AWIPS build 16.2.2 with substantial stability increases. CIMMS staff worked extensively to ensure data archive compatibility with AWIPS builds back to 14.3.1 (the first WES-2 Bridge version available) as this system is the only one that provides for backwards compatibility of archived AWIPS-2 data. For further backward compatibility, development work included preparations for converting AWIPS-1 data archives to AWIPS-2 Bridge accessible formats. An additional development included building initial capabilities to support the AWIPS Graphical Forecast Editor (GFE) in WES-2 Bridge. GFE is the primary tool that forecasters use to prepare and issue forecasts, the majority of routine text forecast products, and long-fuse watch, warning, and advisory products. With the addition of GFE capability, forecasters can use WES-2 Bridge as part of an updated Warning Operations Course (Winter Weather) for a more operationally relevant training experience.

CIMMS also continued to develop and maintain an AWIPS-2 and WES-2 Bridge lab at the WDTD. This unique laboratory environment incorporates centralized command and control of WES-2 Bridge functions. It also features flexible configurability from single-user simulations to multi-user, collaborative simulations where groups of trainee forecasters act as a single WFO and share warning responsibilities. In this mode, one forecaster can issue a simulated warning and his/her partner can modify the warning with updated information, exactly as it happens in real-world NWS operations. No other location on the planet can simulate NWS operations as does this AWIPS laboratory. This lab plays a significant role in the Radar and Applications Course (RAC) workshops.

Additionally, CIMMS staff used this lab in several outreach capacities. Work on the WES-2 Bridge, as well as WDTD's lab, is ongoing.



The WES-2 Bridge software is shown depicting a simulation along with its Simulation Controls and WESSL-2 Event Browser. In this example, WESSL-2 launched a Firefox browser at a specified time to present non-AWIPS data (in this case, a web page containing the Storm Prediction Center convective outlook). WES-2 Bridge interfaces with the AWIPS-2 software, which illustrates preparing a simulated tornado warning using the CAVE, WarnGen and Text Workstation components of AWIPS-2.

9. Weather Event Simulator (WES) Support

Dale Morris, Thao Pham, Phillip Ware, and Alex Zwink (CIMMS at WDTD)

CIMMS staff at WDTD have provided WES support to NWS Weather Forecast Offices (WFOs) since the simulator's inception. As development of the current generation WES-2 Bridge moves forward, technical and logistical WES support for the NWS continues in earnest. Support for the WES-2 Bridge takes many forms. Forecasters can contact CIMMS staff through a variety of tools, such as Google chat, phone calls, direct e-mail, and e-mail list serves. They ask various questions that relate to either general WES-2 Bridge technical issues or help implementing specific WDTD training on these workstations. When necessary, CIMMS staff can access a local office's WES-2 Bridge workstation through a remote connection over the NWS Advanced Weather Interactive Processing System (AWIPS) network. This direct access provides CIMMS staff the ability to directly troubleshoot issues with an office's WES-2 Bridge software. The complexity of the WES-2 Bridge (and its reliance on the routinely changing AWIPS system) makes this level of access crucial to providing quality customer support. Also, CIMMS staff maintain a WES-2 Bridge webpage with technical documentation and other support information for forecasters to access when CIMMS personnel are not immediately available or for solutions to routine problems. CIMMS staff with WES-2 Bridge expertise also provide guidance and support to other CIMMS and NWS instructors at WDTD. In these situations, they provide guidance in AWIPS data collection, WES-2 Bridge simulation development, and case deployment for training. Their aid in these areas, as well as distributing material for training simulations to NWS WFOs, provides a crucial area of support for a variety of WDTD training projects.

While the deployment and transition to AWIPS-2 and the WES-2 Bridge occurred in 2015, the AWIPS-1 version of the WES is still being supported. The WES-1 software (and associated hardware) needs to be maintained so offices can review archived AWIPS-1 case data. WES-1 workstation parts fail occasionally due to hardware age, too. To meet the needs of NWS forecasters, CIMMS staff provided extensive support for installation and troubleshooting of WES-1 software, hardware replacement, and case data. This support will continue until CIMMS finishes development of the WES-1 to WES-2 Bridge format converter tool. This work is ongoing.

10. Warning Operations Course (WOC)/Seasonal Readiness Training – Core Track

Austin Harris, Dale Morris, Stephen Mullens, Phillip Ware, and Andrew Wood (CIMMS at WDTD)

The Warning Operations Course provides blended learning curricula designed to train on warning decision-making techniques that build upon knowledge learned during the Radar & Applications Course (RAC) and other foundational training. The WOC training material covers numerous content areas. The WOC Core Track (WOC Core) contains training on warning decision-making concepts that apply to all weather threats. The WOC Core content can be accessed by students in two ways. Traditionally, forecasters

access all of the WOC Core content sequentially to complete the entire track, usually in the year or two after completing the RAC. Recently, the WDTD has created a new learning initiative known as Seasonal Readiness Training (SRT). With SRT, the WDTD provides forecasters and local training officers with an needs assessment tool with questions related to the WOC content. For any questions the forecaster misses, specific WOC training can be suggested to help the forecaster gain knowledge in these gap areas. By using the SRT needs assessment tool, all forecasters can choose to take a subset of training in a WOC topic area to become more knowledgeable in that topic.

CIMMS staff have worked collaboratively with WDTD instructors on the content and SRT assessment tool for the FY17 WOC Core. Six lessons in this track were authored or updated by CIMMS scientists. In addition to their work on the lesson content, they also provided the questions and feedback for the SRT tool on those modules. Besides their own lessons, CIMMS personnel provided a variety of logistical support, including responding to question from NWS forecasters, reviewing and providing feedback on exercises, assisting local facilitators, creating statistical progress reports for monitoring completions, and providing certificates of completions to students. They also provided extensive assistance during the development and delivery of WDTD's Warning Decision Storm of the Month webinars, which chronicled weather event stories from the Field. These sessions, which continued through April 2017, were an important conduit for NWS forecasters to share experiences and best practices from a single event with their peers.

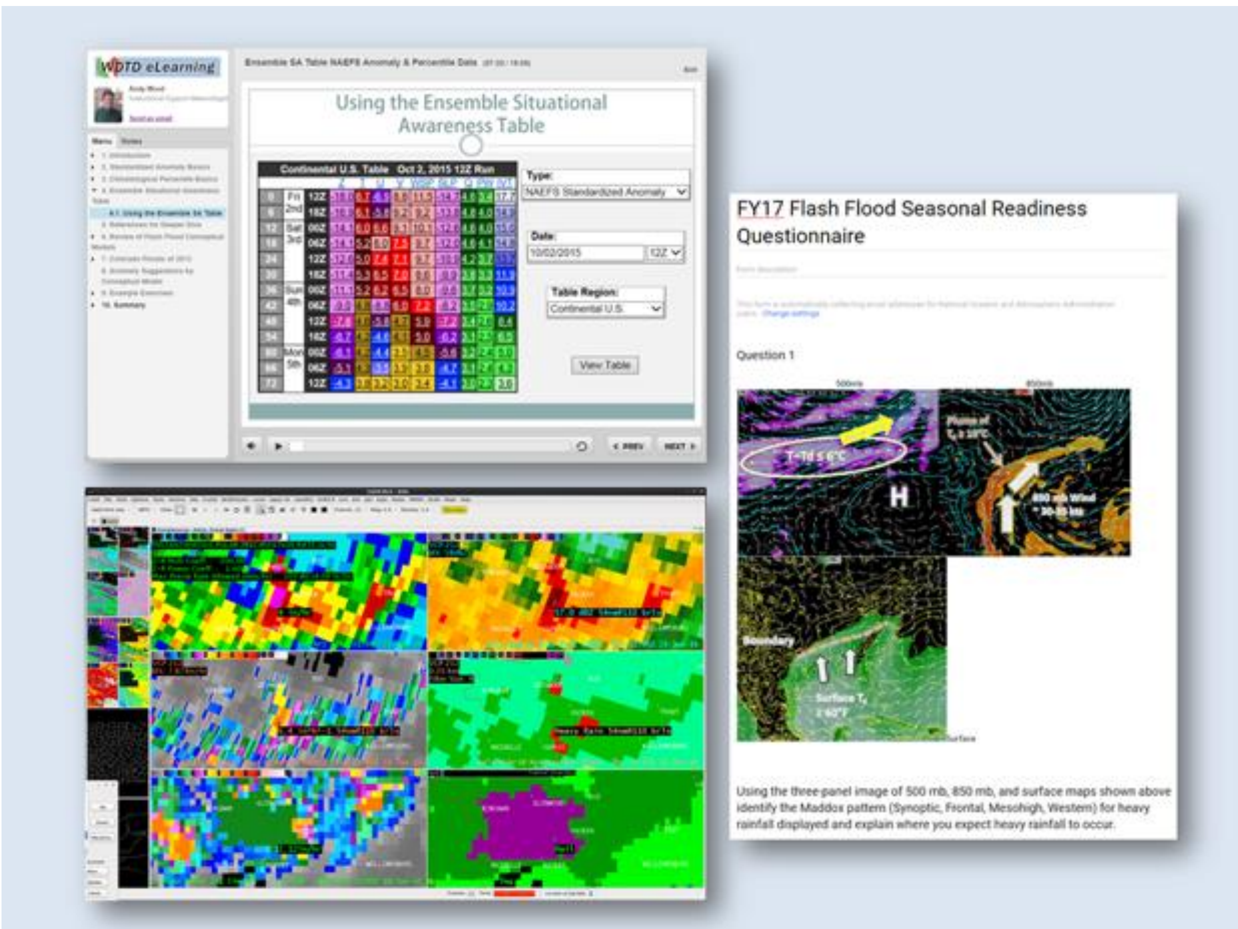
Lastly, CIMMS staff worked in collaboration with WDTD instructors on initial preparations for the FY18 course. This work is ongoing as the FY18 course will be released in January 2018.

11. Warning Operations Course (WOC)/Seasonal Readiness Training – Flash Flood Track

Alyssa Bates, Jill Hardy, Dale Morris, Clark Payne, Chris Spannagle, Andrew Wood, and Alex Zwink (CIMMS at WDTD)

The Warning Operations Course – Flash Flood Track (hereby, WOC Flash Flood) provides training on advanced warning decision-making techniques to every NWS forecaster with flash flood warning responsibility. Throughout the years, CIMMS scientists (in collaboration with WDTD instructors) have been heavily integrated into the development, delivery, and support of WDTD's WOC Flash Flood. A new element of the WOC Flash Flood this year was the Seasonal Readiness Training (SRT) needs assessment tool. This tool provides interested forecasters a method to determine which training they may need prior to the local flash flood season. CIMMS scientists developed these tools as well as cataloging the available training that can help meet these needs. In its initial year, SRT has been very successful in promoting an individualized training plan approach for the WOC Flash Flood that pinpoints the needs of each forecaster.

Numerous updates were made to the WOC Flash Flood by CIMMS scientists this year that strengthened its overall content and hands-on applications. CIMMS staff developed seven new online lessons covering topics such as interpreting climatological data and average recurrence intervals for flash flood forecasting, using web-based tools to improve flash flood responsibilities, and choosing the optimal AWIPS products and settings for enhanced warning operations. Additionally, CIMMS scientists collected and processed data for, as well as co-wrote, a new WES-2 Bridge simulation that highlights the latest improvements in flash flood forecasting and decision-making. These upgrades resulted in nearly 40% of the FY17 WOC Flash Flood being new or significantly updated from previous years, bringing the latest in flash flood research, tools, and best practices to NWS forecasters. CIMMS scientists also managed the delivery of the course, as well as provided logistical support such as responding to questions from NWS forecasters, assisting local facilitators, providing certificates of completion to students, and producing statistical progress reports of students using the Commerce Learning Center (CLC) learning management system. This work is ongoing.



Slide (upper left) shown from a new lesson on using ensembles and anomalies in flash flood forecasting, a screen capture (lower left) shows simulation data on how to compare precipitation sources in AWIPS, and the first question (right) displayed from the FY17 Flash Flood Seasonal Readiness Questionnaire.

12. Warning Operations Course (WOC)/Seasonal Readiness Training – Severe Track

Austin Harris, Stephen Mullens, Chris Spannagle, and Phillip Ware (CIMMS at WDTD), and Michael Bowlan (CIMMS at SPC)

The Warning Operations Course – Severe Track (hereby, WOC Severe) provides training on advanced warning decision-making techniques to every NWS forecaster with severe weather warning responsibility. WOC Severe divides its content into sections on convective fundamentals, lightning, tornadoes, hail, quasi-linear convective systems, and impact-based warnings. A new element of the WOC Severe this year was the Seasonal Readiness Training (SRT) needs assessment tool. With SRT, the WDTD provides forecasters and local training officers with questions related to the WOC content. For whatever questions the forecaster misses, forecasters can take suggested WOC training to gain knowledge and overcome any gaps they have. By using the SRT needs assessment tool, forecasters can choose to take an entire section of training in a WOC topic area to become more knowledgeable in that topic.

For the FY17 release of WOC Severe, CIMMS staff performed several important roles with the course. CIMMS staff updated the lesson templates for all the on-line lessons to improve content readability. They also contributed SRT needs assessment questions and feedback, managed new instructor-led training webinars, and contributed logistical support to the course and its management. This support included responding to questions from NWS forecasters, assisting local facilitators, providing certificates of completions to students, and generating progress reports of students and forecast offices using the Commerce Learning Center (CLC). CIMMS staff played an important role in two other components of WOC Severe. First, CIMMS staff created and managed the Severe Forecast Challenge, an applied learning exercise where forecasters apply concepts learned from the WOC Severe training content in a forecasting environment. In addition to forecasters enrolled in the WOC Severe, the forecast challenge included 326 NWS forecasters this year who issued over 12,500 individual forecasts. Second, CIMMS personnel also provided extensive assistance during the development and delivery of WDTD's Warning Decision Storm of the Month webinars, which chronicled weather event stories directly from NWS forecasters. CIMMS support of these webinars included providing feedback to presenters during dry run sessions prior to the webinar, record audio and video from live webinar, manage phone connections during the webinar, and post-process the recorded webinar for online playback for those who couldn't attend live.

Lastly, CIMMS staff worked in collaboration with WDTD instructors on initial preparations for the FY18 course. This work is ongoing as the FY18 course will be released in January 2018.

Severe Weather Forecast Challenge web page.

13. Warning Operations Course (WOC)/Seasonal Readiness Training – Winter Track

Alyssa Bates, Stephen Mullens, Matt Sienkiewicz, and Chris Spannagle (CIMMS at WDTD)

The Warning Operations Course – Winter Weather Track (hereafter, WOC Winter Weather) has been under development at the WDTD after a prolonged hiatus for an initial re-release in September 2017. As part of this re-release, CIMMS staff worked with WDTD instructors and subject matter experts from universities and the NWS to develop the FY17 Winter track content. Lessons from the previous WOC Winter were updated. Additional topics were identified, and new content developed. CIMMS staff coordinated these development efforts with many of the subject matter experts and reviewers, provided feedback to the developers, and developed evaluation material.

In addition to these development efforts, CIMMS staff collaborated with WDTD instructors and NWS national headquarters on a new initiative called Hazard Simplification. As part of this initiative to simplify winter weather products starting in the Autumn of 2017, CIMMS personnel coordinated a series of training webinars with the Hazard Simplification team. This work included reviewing presentation material, hosting the webinars, recording the live webinars, and post-processing the recorded webinar as a video for those who could not attend the live sessions. This work is ongoing.

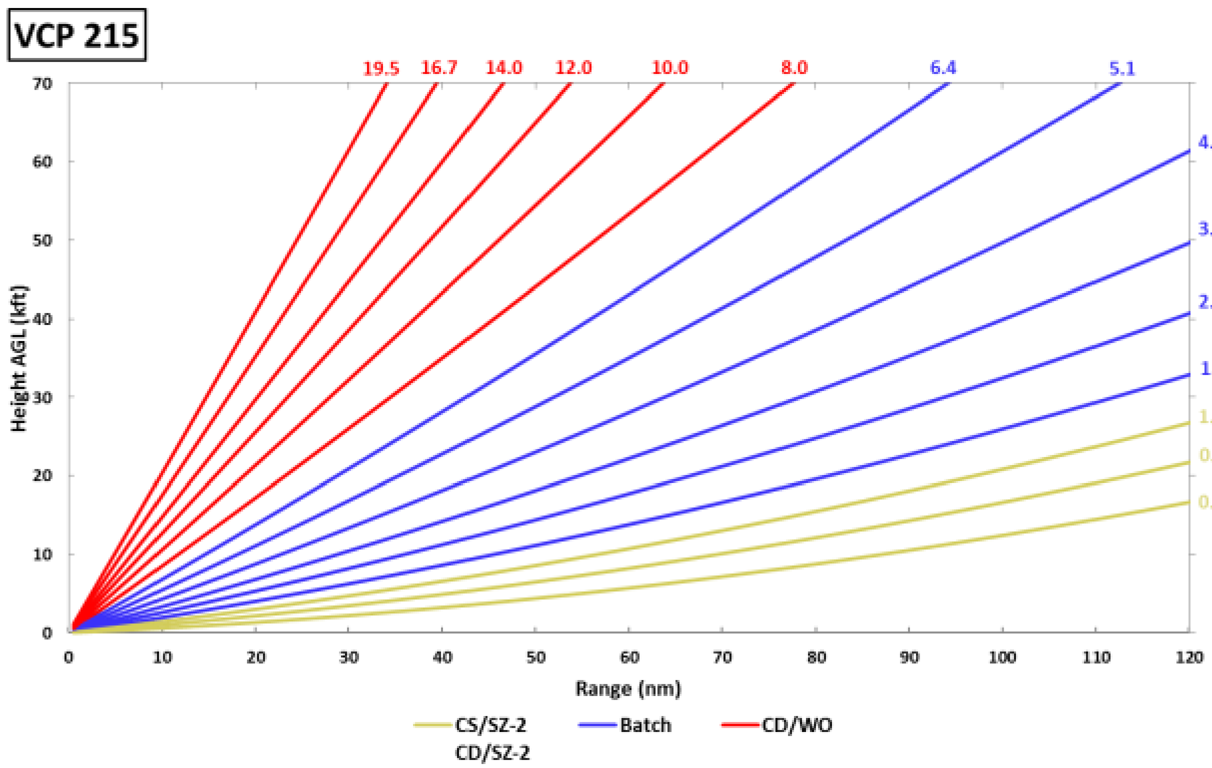
14. Weather Surveillance Radar – 1988 Doppler (WSR-88D) Build Improvement Training

Clark Payne, Andrew Wood, and Brad Workman (CIMMS at WDTD)

The WSR-88D radars upgrades occur routinely, approximately once a year during its life cycle to maintain the system and integrate new science and technology. As these build updates to the system occur, CIMMS personnel work closely with WDTD instructors and partners at the Radar Operations Center (ROC) during training development and delivery for NWS staff. Additionally, the WSR-88D training can be accessed by NWS partners who work with the radar. CIMMS work on this project includes supporting training development and delivery, making various radar training courses easily available for NWS partners (including dual-polarization radar technology training), and collaborating with experts to help optimize Routine Product Set (RPS) lists at NWS weather forecast offices (WFOs) nationwide.

During the past year, no system upgrades occurred with the WSR-88D. However, CIMMS staff continued to support the development of training for the next build upgrade (Build 18.0), which begins Beta test in the Autumn of 2017 and gets implemented in 2018. Changes contained in this update are significant, including removal of most previously existing Volume Coverage Patterns (VCPs), the implementation of multiple new VCPs, increasing the dynamic nature of VCPs by implementing Mid-volume Rescan of Low-Level Elevations (MRLE) functionality on a test basis, and significant operating system and Human Control Interface upgrades.

This work is ongoing as the WSR-88D continues to receive periodic software and hardware upgrades.



Schematic shows the elevation angles in one of the new Volume Coverage Patterns (VCP 215) that will be introduced in RDA/RPG Build 18.0.

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OST Project 13 – Research on Integration and Use of Multi-Sensor Information for Severe Weather Warning Operations

NOAA Technical Lead: Stephan Smith (NOAA OST)

NOAA Strategic Goal 2 – *Weather-Ready Nation – Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Task II

Objectives

Work with CIMMS/NSSL scientists in developing multiple-radar/multiple-sensor (MRMS) severe weather warning applications and advanced display systems and transferring that technology to NWS operational systems; collaborate with the NOAA Hazardous Weather Testbed - Experimental Warning Program at the National Weather Center in Norman.

Accomplishments

1. General Overview

Greg Stumpf (CIMMS at OST/MDL/DAB)

The 13th full year of the CIMMS/NWS-Meteorological Development Laboratory (MDL) scientist position was completed during this review period. This project (OST13) has been conducted by the CIMMS/MDL scientist throughout this period.

The CIMMS/MDL scientist remained the liaison between the NOAA Hazardous Weather Testbed's (HWT) Experimental Warning Program (EWP) and NWS-MDL. The EWP is a proving ground for evaluating new applications, technology, and services designed to improve NWS short-fused (0-2 hour) hazardous convective weather warning decisions. He continues to collaborate with National Severe Storms Laboratory (NSSL) scientists who are involved in the EWP, including attending scientific and technical meetings.

The CIMMS/MDL scientist continues to be involved with the severe weather warning R&D activities at CIMMS and NSSL and served as a co-principal investigator and subject matter expert for the multiple-radar / multiple-sensor (MRMS) severe weather warning products. The process to transfer MRMS technology to operations at the National Center for Environmental Prediction was completed in FY15, and the CIMMS/MDL scientist has been involved in the following activities related to the MRMS tech transfer, 1) MRMS point-of-contact for NWS Office of Science and Technology, 2) development manager for creating the capability to display operational MRMS products in the National Weather Service AWIPS2 system, and, 3) supporting the collaborative MRMS "community" on the NOAA Virtual Laboratory (VLab).

2. MRMS Product Display for AWIPS2

Greg Stumpf (CIMMS at OST/MDL/DAB), and Darrel Kingfield and Tiffany Meyer (CIMMS at NSSL)

The operational MRMS system at NCEP went online and began disseminating data to the weather enterprise, including the National Weather Service, on 1 October 2014. The CIMMS/MDL scientist is the development manager overseeing an NSSL employee doing the software coding. Some minor changes in the source code to display MRMS products were implemented during FY17. In the role of the MRMS display development manager for AWIPS2, the CIMMS/MDL scientist continues to work with with NCEP implementation teams to monitor MRMS data transmission latency.

3. MRMS in the NOAA Virtual Laboratory (VLab)

Greg Stumpf (CIMMS at OST/MDL/DAB)

The CIMMS/MDL scientist is the site owner of the MRMS community in the NOAA Virtual Laboratory (VLab). He developed the design and layout of the collaboration community and manages the development community. The scientist coordinated the development of an MRMS product Wiki in the VLab, designed as a basis for official NWS/WDTB training documentation. In addition, the CIMMS/MDL scientist serves on the VLab Support Team, to help design, develop, and implement the NWS VLab as a whole. The CIMMS/MDL scientist leads the bi-monthly NOAA VLab Community and Project Owners' Meetings.

4. Hazard Services – Probabilistic Hazard Information (HS-PHI)

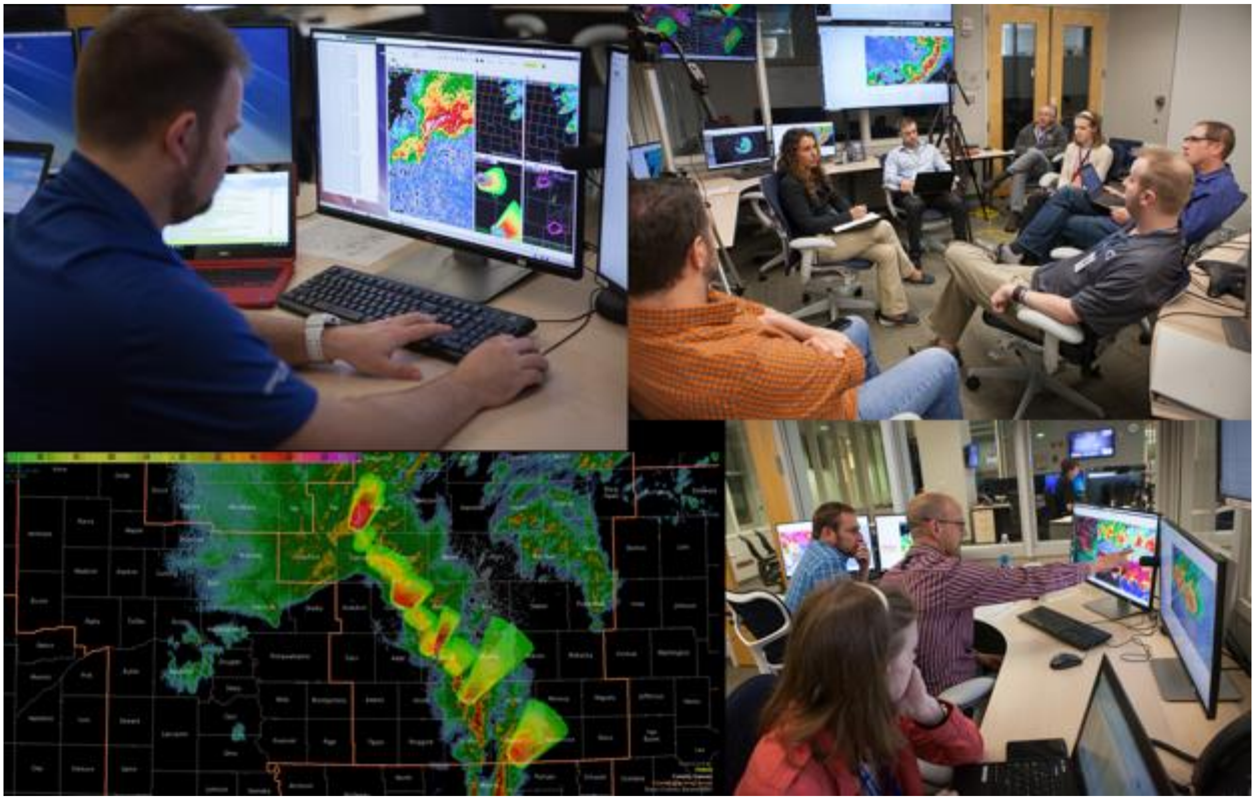
Greg Stumpf (CIMMS at OST/MDL/DAB) and Tiffany Meyer (CIMMS at NSSL)

The CIMMS/MDL scientist is co-team leader, along with a NOAA/ESRL/Global Systems Division (GSD) software engineer, to transfer the technology of the NSSL-developed Probabilistic Hazard Information (PHI) Prototype tool. The PHI-Prototype has been under development since 2013 and has been tested in the NOAA HWT during the springs of 2014-2017. Feedback on the software design, operational use, and human factors workload, was used to improve the prototype each year. MRMS products were available within the PHI tool to aid in the forecaster decision making process. Beginning after the 2015 experiment, GSD software developers and meteorologists began implementing the PHI Tool concepts into AWIPS2 Hazard Services, a new application platform from which all NWS watches, warnings, and advisories will be issued in the new future. The CIMMS/MDL scientist led a 3-week NOAA HWT experiment for the second year in a row, conducted in March and April 2017, using visiting NWS forecasters to test this new Hazard Services – PHI (HS-PHI) application. This included helping guide the GSD software development, selection of archive case scenarios designed to train forecasters on the HS-PHI software and PHI concepts, and test various operational decision making situations including inter-office collaboration.

Warning Decision Training Division scientists also collaborated on the experiment, in order to start the process of developing best operational practices. Forecasters used HS-PHI in 6-7 archived weather events in displaced real-time scenarios, which included severe pulse storms, hail storms, tornadic supercells, squall lines, bow echoes, and QLCS tornadoes. The evaluation included a human factors component collecting forecaster workload data. The figure below shows a screen capture of the HS-PHI application, as well as forecasters and researchers working together in the experiment.

Over the past two years of development, we have brought the software to about 85-90% compliance with the 2015 baseline version of the NSSL PHI Prototype. Since the HWT experiment concluded, work has been underway to identify the remaining 2015 baseline functionality and develop a plan to complete that work. This included bi-weekly coordination meetings, as well as a week-long code "sprint" conducted at GSD in Boulder with all of the developers – an intensive test and debug session.

We have also identified new functionality for HS-PHI, including 1) components that have been developed and evaluated using the PHI Prototype in 2016 and 2017, and 2) additional functionality identified via forecaster feedback during both the HS-PHI and PHI Prototype exercises. Once the work to bring HS-PHI in compliance with the 2015 baseline is complete, the new functionality candidates will be ranked and implemented for Year 3 of testing in the HWT as time and scheduling permits. One of the initial new functionalities will be the addition of Lightning PHI (both guidance and forecast grid creation). In addition, we will develop an intermediate solution to smoothly phase the warning paradigm from the current NWS warnings and fully-implemented PHI known as "Threats-In-Motion" (TIM) which are deterministic storm-following warning polygons that update at one-minute intervals. TIM has been shown to double location-specific lead times by giving all locations downstream of storms more equitable lead times. TIM also automatically clears out warnings after the events of passed, effectively reducing "departure time" to near zero.



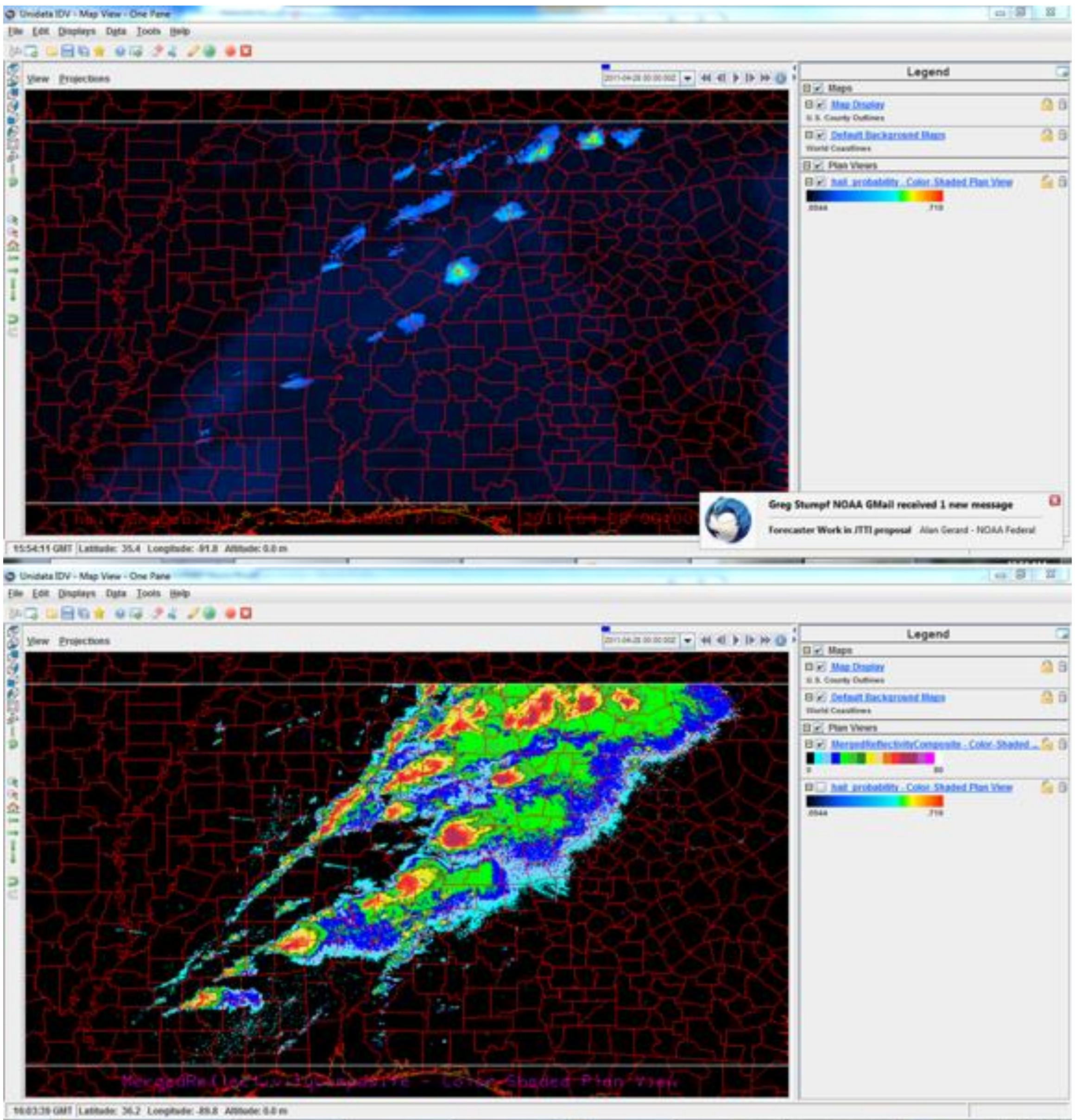
Images from the Hazard Services – Probabilistic Hazard Information (HS-PHI) 2017 spring experiment in the NOAA Hazardous Weather Testbed, including various forecaster and researcher interactions with the software and during group discussions. Also shown is screen capture of the HS-PHI application, showing probabilistic tornado "plumes" for a Quasi-Linear Convective System (QLCS).

5. Probabilistic Hazard Information (PHI) Verification

Greg Stumpf (CIMMS at OST/MDL/DAB) and Brandon Smith (CIMMS at NSSL)

The CIMMS/MDL scientist is co-investigator, along with scientists at NOAA/ESRL/GSD, to develop a real-time verification system for the PHI Tool, which will use 1) a new way to blend, in real-time, remotely-sensed data from the MRMS system with live storm reports, and 2) innovative warning verification techniques that have been under development for several years, which include new measures such as False Alarm Area and False Alarm Time in verified warnings as well as location-specific lead- and departure-time. A gridded verification system for severe thunderstorm reports (hail $\geq$ 1" diameter and/or wind $\geq$ 25 ms^{-1}) was completed. The system scores both severe thunderstorm warnings and tornado warnings against ground observations of severe hail and wind on a 1 km^2 x 1 min grid (figure below), and calculates grid-based Probability of Detection, False Alarm Ratio, Lead Time, and new metrics False Alarm Area, False Alarm Time, and Departure Time. The system has been run on the entire storm-based Severe Thunderstorm Warning and Tornado Warning and Local Storm Report database from October 2007 – December 2016.

GSD completed the initial development of a model which blends Multiple-Radar/ Multiple-Sensor (MRMS) Maximum Estimated Size of Hail (MESH) fields, RAP model data, and local storm reports to create a probabilistic hail observation grid (figure below). The model was delivered to CIMMS and after some minor modifications, has been successfully run. The next step is to refine the verification code to score probabilistic forecasts (PHI) against probabilistic observations, and then convert this to a real-time application to be run in the HWT during the spring of 2018, in conjunction with the HS-PHI experiment.



Output from the 27 April 2011 super-outbreak event over the southeast U.S.: (top) The GSD Probabilistic Hail Observation Model (bottom) corresponding composite reflectivity (maximum reflectivity in the vertical column).

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ARL Project 15 – Weather and Climate Change Monitoring and Research Support of the Atmospheric Turbulence and Diffusion Division of NOAA's Air Resources Laboratory

NOAA Technical Lead: Sarah Roberts (NOAA ARL/ATDD)

NOAA Strategic Goal 2 – *Weather-Ready Nation – Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Task II

Objectives

The Atmospheric Turbulence and Diffusion Division (ATDD) of the Air Resources Laboratory (ARL), in the National Oceanic and Atmospheric Administration (NOAA), plays a vital role in performing research and development on three principal themes: atmospheric chemistry and deposition, climate observations and analysis, and boundary-layer characterization. ATDD also provides critical expertise in delivering high quality data from climate reference networks and boundary layer instrumentation. These networks and instrumentation contribute to improved understanding of climate variability and change across the U.S. and to improved understanding and prediction of weather systems. Advances in observational and analytic techniques of boundary layer measurements and climate observing systems are essential to scientific climate research. Furthermore, they provide national and regional-scale data required by several sectors of the economy, in particular, the water and energy resources management industries. NOAA's ATDD and Oak Ridge Associated Universities (ORAU) are primarily responsible for ensuring these climate observing systems deliver climate-quality data for NOAA. In addition, the ATDD-ORAU partnership conducts research at the weather-climate interface, including regional climatology, renewable energy, satellite calibration/validation, and meteorological and chemical measurements, to help evaluate the impact on land surface changes and climate.

Accomplishments

1. Boundary-Layer Characterization

Edward Dumas, Ronald Dobosy, Mark Heuer, Randall White, David Senn, and Praveena Krishnan (ORAU), and Temple Lee and Michael Buban (ORAU Post-Docs)

a. Unmanned Small-Aircraft Systems (sUAS) Testbed

Coyote: The Coyote is an air-launched military sUAS being repurposed by NOAA to measure within the eyewall of a hurricane, especially at low altitude over the sea. A Coyote aircraft was delivered to ATDD for calibration tests of its current iMET-XF instrumentation. Sensor systems from three Coyote nose cones were tested under controlled temperature and relative humidity (T/RH) conditions at multiple set points in ATDD's Thunder Scientific chamber to characterize their response. Thunder Scientific chambers are traceable to the National Institute of Standards and Technology (NIST). A complete report was generated and sent to the project director, Dr. Joseph Cione, NOAA/Atlantic Ocean Marine Laboratory/Hurricane Research Division (NOAA/AOML/HRD).

Ed Dumas and Mark Heuer traveled to Raytheon in Tucson, Arizona, on February 7, 2017, to be trained on the installation and removal of the iMet-XF payloads. This allowed testing of the Coyote sUAS iMet-XF instrumentation under simulated operational conditions. In late May 2017, a Coyote airframe was mounted into a test fixture on a pickup truck. The test fixture, shown in the figure below, included a Vaisala T/RH sensor used as the reference. Five iMet-XF systems were tested during May 22-25, 2017. During each test, the truck was driven at approximate flight speeds (50 knots, 57 MPH) while data from the iMet-XF was collected through the aircraft transmitter and ground station. This simulated the environment to which the instruments will be subjected in flight.

Four channels were tested for each sensor: Air temperature, Humidity, Air pressure, and Infrared (sea) temperature. Ground speed was also measured and recorded. A high fraction, 20 percent, of the sensors exhibited unacceptable behavior in one or more channels. The instruments were returned to Ratheon for resolution. A complete report was provided to Joseph Cione. Although issues were discovered, resolution was still possible.

Coyote Road Test.

<u>MD4-1000 and DJI S-1000</u>: The MD4-1000 four-motor rotary wing sUAS, shown in the first figure below, and the DJI S-1000 eight-motor rotary wing sUAS, shown in the second figure below, are each about 1 m across with radially arrayed rotors. Both are NOAA property (the DJI belonging to NOAA/ATDD and the MD4 belonging to NMFS/Cooperative Center for Unmanned Technology, Santa Barbara, California) and are available to ATDD by cooperative agreement. The two aircraft were flown at the Knox County Radio Control (KCRC) model flying field on August 29, 2016, to compare the performance of two identical and calibrated iMet-XQ temperature/relative humidity/pressure (T/RH/P) sensors mounted on these two platforms under nearly identical conditions. The KCRC model flying field is shown below.

Because only one pilot was available, the aircraft were flown in succession. The flights were separated by approximately 20 minutes. The late afternoon deployment, between 15:10 and 16:00 local time, took advantage of relatively constant planetary-boundary-layer characteristics.

The MD4-1000 flight comprised two vertical profiles in 18 minutes between the surface and 365 meters, including a period of hovering near the KCRC tower. The S-1000 flight completed one profile in 13 minutes from the surface to 365 meters, also including a period of hovering near the KCRC tower. Each sensor collected latitude, longitude, altitude, time, temperature, relative humidity, and pressure data at 1 Hz. An important discovery was the lower overall variation between the sensors during ascent relative to decent.

An additional test location was established at House Mountain Radio Control (HMRC) model flying field in Corryton, Tennessee, offering a large flat, homogeneous grass field that was ideal for testing sUASs. In particular, HMRC features a longer runway than KCRC to better accommodate a larger fixed-wing sUAS. The HMRC model flying field is shown below.

ATDD received permission to fly the S-1000 and other sUASs at the HMRC field on November 14, 2016. On December 16, 2016, ATDD installed two surface flux towers to measure heat flux and surface temperature. Infrared (IR) imagers were then flown to measure the variability of surface temperature around the towers, as well as T/RH variability in the atmosphere, to better estimate variability of surface heat flux over the surrounding grass field.

Seven flights, four with the S-1000 and three with the MD4-1000, were completed. The S-1000 performed profiles measuring temperature and relative humidity (T/RH) over each tower, also collecting IR images of surface temperature over each tower at the top of each profile. The MD4-1000 flew horizontal transects between the towers at 2m, 10m, 25m, 75m, 125m, 175m, 225m, and 275m above ground. The results have been submitted for publication in the *Journal of Atmospheric and Oceanic Technology*.

Ed Dumas and Temple Lee attended the National Center for Atmospheric Research (NCAR) small UAS symposium with ATDD Director Bruce Baker on February 20-24, 2017. Ed Dumas and Bruce Baker each chaired several sessions to discuss the interplay of current and future UAS capabilities from scientific, regulatory, operational, and platform-specific viewpoints. The purpose of the conference was for NCAR to get feedback about its role in using UAS for its mission to serve academic and government institutions. There were nearly 100 attendees from academic, private, and government entities that represented a cross-section of UAS operators and researchers.

Ed Dumas attended the American Meteorological Society annual meeting in Seattle, Washington on January 22-26, 2017. He displayed Air Resources Laboratory's (ARL's) DJI S-1000 small UAS for the week at the NOAA booth in the exhibit hall. Ed Dumas and Bruce Baker gave a tag-team presentation to highlight the S-1000's capabilities and its use in the VORTEX-SE 2016 field campaign. Ed gave a paper in the special UAS session on Thursday to present the results from the DJI S-1000 profile flights during the VORTEX-SE 2016 field campaign.

The MD4-1000 four-motor rotary wing sUAS.

The DJI S-1000 eight-motor rotary wing sUAS.

The Knox County Radio Control (KCRC) model flying field.

The House Mountain Radio Control (HMRC) model flying field.

<u>Penguin BE</u>: The Penguin BE fixed-wing sUAS arrived at ATDD on June 21, 2017. It was evaluated and then shipped to BlackSwift Technologies in Boulder, Colorado for autopilot installation and test flights. Steve Brooks and a graduate student from UTSI visited ATDD the following day and made measurements of the payload bay of the aircraft in preparation for instrument installation. The figure below displays a picture of the aircraft just after it was assembled at ATDD.

Penguin BE after it was assembled at ATDD.

b. VORTEX-SE 2017

ATDD is participating in the VORTEX-SE 2017 experiment in the vicinity of Huntsville, Alabama to study the genesis of severe storms and tornadoes in the southeastern U.S. Flights of both the DJI S-1000 and MD4-1000 were made at KCRC's model flying field on March 8, 2017 to compare temperature and relative humidity as a function of altitude with the ATDD tethersonde in preparation for VORTEX-SE. Each aircraft was flown in turn adjacent to the tethersonde. The DJI S-1000 was flown on March 25**th** and March 27th as part of intensive operating period (IOP) 1 and IOP 2 to capture temperature and humidity profile data to an altitude of 213 m above ground level (AGL) in Cullman, Alabama.

The DJI S-1000 small Unmanned Aircraft System (sUAS) was used to measure temperature and humidity profiles in the lower 213 m of the atmosphere and to map the earth's surface temperature using an IR imager (FLIR) during four intensive observation periods (March 25th & 27th and April 5th & 28th). ATDD and NOAA/OMAO/AOC personnel also flew the Microdrone MD4-1000 sUAS during the April 28th intensive. During this intensive, four MD4-1000 flights were flown simultaneously with the DJI

S-1000. Mark Rogers from NOAA/AOC was pilot-in-command of the MD4-1000 during the simultaneous flights.

DJI S-1000 flights were made at different times during each day. Nineteen flights were made with the DJI S-1000 sUAS. Six flights were made with the Microdrone MD4-1000 sUAS. Flights 1 and 2 with the MD4-1000 were performed for pilot checkout and orientation. No meteorological data was collected during those flights. The sUAS flights in Cullman were made primarily to measure atmospheric temperature profiles and surface temperature. No flights were made this year for tornado storm damage assessment. Note four of the flights in Cullman, on April 28, 2017, were made simultaneously with the Microdrone MD4-1000 and the DJI S-1000.

c. Summer Science Academy of the Appalachian Regional Commission (ARC)

The ARC and Oak Ridge Associated Universities (ORAU) sponsored their annual Summer Science Academy in Oak Ridge for middle-school science students in July 2017. A primary activity was wind generation of electric power. On a field trip, the students visited one of the fifteen full-scale wind turbines operated by Invenergy located on Buffalo Mountain above Oak Ridge. They built their own model wind turbines on a commercial model generator hub. The students displayed their creativity when they designed their own blades and constructed them of dowels, balsa wood, and corrugated plastic sheet. At the end of the session, they went to NOAA's Atmospheric Turbulence and Diffusion Division to use ATDD's wind tunnel to test the effectiveness of their designs. The testing was enhanced with discussions from two ORAU engineers located at ATDD (Randy White, aerospace engineer, and Dave Senn, electrical engineer).

There was a competition for bragging rights over whose design could produce the most power over a standard 10 settings of wind speed in the outflow region of the wind tunnel. The activity was exciting for everyone and gave a practical demonstration that some designs are better for low wind and others for strong wind. There was generally a large range of power produced, depending on the blade design, which provided an opportunity to explain why some designs are better than others. The figure below shows four images: (1) students outside with wind turbines, (2) full-scale (80-meter hub height) wind turbines, (3) wind turbine named “Comma” ready for test, and (4) “Comma” after mechanical failure.

Students outside with wind turbines

Wind turbines

“Comma” ready for test

“Comma” failure

Summer Science Academy of the Appalachian Regional Commission (ARC).

2. Atmospheric Chemistry and Deposition

Simone Klemenz and Mark Heuer (ORAU)

Development of new parameterizations describing the emission potential of soil and stomatal pathways, as a function of nitrogen status, is ongoing under direction of NOAA/ATDD scientist Dr. LaToya Myles. Data collected during the 2014 collaborative field study with the University of Illinois at Urbana-Champaign has been used in the development of these parameterizations for the SURFATM-NH3 model, which is a bi-directional model that simulates fluxes between biogenic surfaces and the

atmosphere. Initial results are promising, with further refinement needed to more accurately estimate ammonia fluxes.

a. Chemical Analysis at ATDD

A wet-chemistry laboratory is maintained at ATDD for analysis of atmospheric samples collected during field expeditions. Ammonia, sulfates, nitrates, ozone, and other atmospheric constituents having environmental consequences are analyzed using ion chromatography in the lab and other chemical processes in the field. The equipment is maintained by ORAU employee, Simone Klemenz, partially supported by the CIMMS project.

With every precipitation event, rain samples are collected from ATDD's long-standing ridgetop site of AIRMoN. These are analyzed for multiple anions and cations deposited by the rain, an activity that has been ongoing since at least the 1980s. This routine, episodic, and relentless task is the charge of Simone Klemenz, with assistance from one of a list of substitutes she maintains, recruited from other ORAU employees partially supported by the CIMMS project. After the wet-chemistry analysis, the samples are shipped to the National Atmospheric Deposition Program (NADP) headquarters in Champaign-Urbana, Illinois. During dry periods, the sample buckets exposed on the ridge are changed, and field blanks are performed every seven days. The site is also winterized every year for the cold season.

3. Climate Observations and Analyses

Timothy Wilson and Ronald Dobosy (ORAU)

a. Flux Observation of Carbon from an Airborne Laboratory (FOCAL)

The Flux-Fragment Method (FFM) selected for analysis was introduced by ARL and the University of Alabama in a 2008 publication in *Agricultural and Forest Meteorology*, but is not widely known compared to the rival wavelet method. Both methods are able, from different bases, to characterize the flux (e.g., emission of methane) from surface features, which are much smaller than an acceptable averaging length. Such features are characteristic of the North Slope of Alaska. A second generation of the FFM, upgrading the uncertainty analysis for fluxes, has been submitted to the *Journal of Atmospheric and Oceanic Technology*. This upgrade addresses a number of statistically questionable assumptions of the earlier version providing a more defensible estimate.

FFM is a conditional-sampling technique effective for computing fluxes from flights over surfaces having repeated small features, otherwise obliterated in the necessary averages. Two papers have been accepted for publication related to the FOCAL aircraft (Flux Observations of Carbon from an Airborne Laboratory) and its 2013 field campaign in Alaska. One has appeared in early online release by the *Journal of Atmospheric and Oceanic Technology.* The other is expected to appear in *Atmospheric*

Chemistry and Physics within a month. The FOCAL is a collaboration led by Harvard University and including ATDD and Aurora Flight Sciences, Inc.

In a 2013 campaign, the FOCAL successfully measured the emission of methane and water vapor over a wide range of tundra on Alaska's North Slope between Prudhoe Bay and Barrow. FOCAL's innovation is to carry a gas analyzer, which can sample at a high enough rate for eddy covariance from a small minimally intrusive aircraft, but also measure the mix of isotopologues in the gases being sampled. These two papers demonstrate the ability of the system to measure ordinary fluxes of total gas (all isotopologues) over an area on the order of (100 km)^2. The fluxes match in general with those measured from fixed sites and, in particular, with those from a surface site established for intercomparison. They also provide an improved estimate of the random uncertainty in flux analyzed using the flux-fragment method (FFM), as well as a theoretical comparison of the assets and liabilities of the FFM with those of the more widely accepted method of wavelet analysis.

These are two approaches to the challenging and important analysis of the spatial patterns of fluxes measured from the air over heterogeneous landscape. The type of instrument suite and data analysis demonstrated in these papers, combined with fixed and remote sensors, is well suited to quantifying the emissions of methane and other greenhouse gases and their change with time over large, difficult-to-reach areas in the remote and demonstrably warming arctic.

b. Climate Reference Network (CRN)

For Alaska CRN, one site was installed at Yakutat, and 10 Annual Maintenance Visits (AMVs) were made. Seventeen AMVs and one Unscheduled Maintenance Visit (UMV) were made throughout the U.S., July – September 2016

CRN staff visited 20 sites October – December 2016, making 16 AMVs, one installation, and three UMVs.

CRN staff made 24 AMVs January – March 2017.

Files are retrieved as necessary by ATDD to fill data gaps at individual CRN sites receiving AMVs or UMVs. These files are maintained on the server ftp.atdd.noaa.gov for retrieval by the National Centers for Environmental Information (NCEI). Instrument data for each site are maintained in the database ISIS (Integrated Station Information System) on NCEI's server, along with a record of events that affect data quality. New ISIS events are identified from ATDD's field crews and archived data.

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CIMMS Task III Project – Contribution to Model Development and Enhancement Research Team by the Center for Analysis and Prediction of Storms

Ming Xue, Gang Zhao, Chengsi Liu, and Youngsun Jung (CAPS)

NOAA Technical Lead: Stan Benjamin (NOAA ESRL/GSD)

NOAA Strategic Goal 2 – *Weather-Ready Nation: Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Task III

Objectives

Develop and test an ensemble Kalman filter (EnKF) and GSI-based EnKF/3DVAR hybrid data assimilation system suitable for operational implementation in the Rapid Refresh (RAP) forecasting system.

Accomplishments

Under the support of this and another related grant, the CAPS group established a regional dual-resolution (DR) (40/13km) ensemble square-root filter (EnSRF) – 3D ensemble variational (3DEnVar) coupled hybrid data assimilation (DA) system. The DR DA system was tested with 3-hour cycles over the same 9-day testing period used in Zhu et al. (MWR 2013) and Pan et al. (MWR 2014). The optimized DR hybrid system

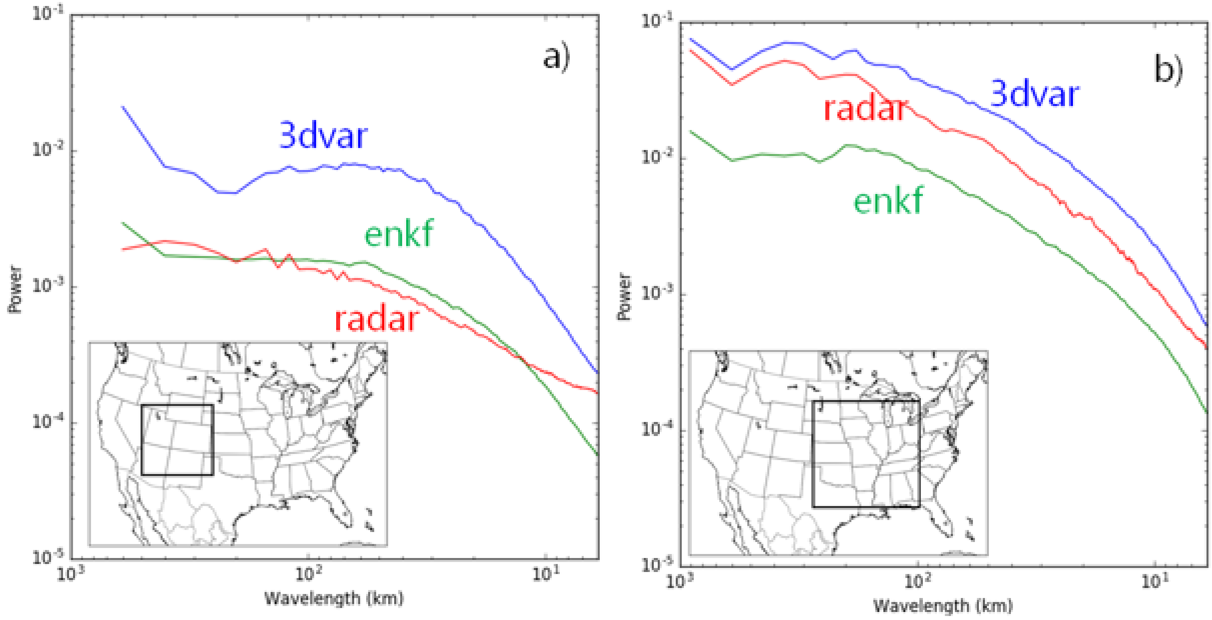
was found to significantly outperform the 13-kmm GSI-3DVar. Its forecasts are also better than those from interpolated LR hybrid analyses for the humidity and wind but not for temperature. For precipitation forecasts, the DR hybrid always outperforms GSI-3DVar, and outperforms the LR hybrid except for the initial period and for low thresholds (see figure below). The humidity fields are improved most. Pan et al. (2017) is being revised for submission.

The CAPS group also investigated the impacts of assimilating satellite radiance data by using the regional GSI-based EnKF DA system, which was documented in Zhu et al (2013 MWR) without including satellite data. The satellite radiance data examined include those of the Advanced Microwave Sounding Unit (AMSU), the Atmospheric Infrared Sounder Radiance (AIRS), the Microwave Humidity Sounder (MHS) and the High-resolution Infrared Radiation Sounder (HIRS) data. Positive impacts of radiance data are obtained after tuning the radiance bias correction with appropriate data thinning. Among the radiance datasets, AMSU-A and AIRS data show the greatest positive impacts. AMSU-A data improve the forecasts of all verified variables especially for wind while AIRS data greatly improve the forecasts of humidity. When all radiance data are assimilated, the forecasts are improved even more. Parallel experiments are also performed with GSI 3DVar, and positive impacts are also obtained but forecasts from the EnKF analyses are consistently better than those from the 3DVar analyses. Precipitation forecast skills on the downscaled 13 km grid are also improved with radiance assimilation. Zhu et al (2017) is being revised for resubmission to JAMES.

Another important piece of work partially supported by this grant is the development of capabilities to directly assimilate radar data within GSI 3DVar and GSI En3DVar systems, and test them for convective-scale predictions. During the 2017 Hazard Weather Testbed (HWT) Spring Experiment, CAPS ran the GSI-based EnKF system with hourly cycles on 3-km CONUS grid for 6 hours, and assimilated radar data at 15-min intervals in the final hour, to initialize forecasts at 0000 UTC each day during the experiment period. Preliminary verifications suggest that the forecasts launched from the EnKF analyses are more skillful than the forecasts launched from analyses obtained using the ARPS 3DVAR/cloud analysis system.

The figure below shows the 1D rainfall power spectra from the hourly accumulated precipitation of EnKF-based ensemble (green) compared with those of the 3DVAR-based ensemble (blue) and the Multi-Radar Multi-sensor (MRMS, red) precipitation estimate over the mountainous area and the central US. Overall, the 3DVAR-based ensemble over-predicts precipitation at all scales whereas the EnKF-based ensemble under-predicts precipitation compared to the MRMS during the first few forecasting hours. In the mountainous area, the 3DVAR-based ensemble produces a lot of spurious precipitation whereas the power spectra from the EnKF-based ensemble is more similar to that of the MRMS at scales greater than about 20 km but drops off faster than the MRMS at the smaller scales. In the central US domain, the EnKF-based ensemble presents significantly lower power than the 3DVAR-based ensemble and MRMS, but all three exhibit similar scaling behaviors although the magnitudes are different. The EnKF

DA system is being further tuned to hopefully further improve its performance for 3-km CONUS grid.



Spectra from EnKF (green), 3DVAR (blue), MRMS (red) hourly rainfall accumulations over a) the mountain and b) Central US domains. The spectra are temporal averages over 17 cases and 9 ensemble members during the HWT between 0100–0300 UTC, corresponding 1–3 hour forecasts. The geographical domains used in the spectral analysis are shown in the lower left corner of each plot.

Publications

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CIMMS Task III Project – Advanced Data Assimilation and Prediction Research for Convective-Scale "Warn-on-Forecast"

Ming Xue, Youngsun Jung, Tim Supinie, Chengshi Liu, Rong Kong, and Marcus Johnson (CAPS)

NOAA Technical Lead: Pamela Heinselman (NSSL)

NOAA Strategic Goal 2 – *Weather-Ready Nation: Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Task III

Objectives

A key component towards achieving the 'Warn-on-Forecast (WoF)' vision (Stensrud et al. 2009; Stensrud 2010) for severe weather is to obtain sufficiently accurate initial conditions of convective-scale numerical weather prediction (NWP) models. Advanced data assimilation (DA) is the essential procedure for obtaining such initial conditions. To realize probabilistic forecasting, which is also a key part of the WoF vision, an ensemble of initial conditions is needed to initialize the ensemble forecasts. As a partner of the WoF project, most of its efforts on developing, refining and applying ensemble-based data assimilation systems to storm-scale deterministic and probabilistic predictions. Efforts will also be made to develop a hybrid ensemble-variational data assimilation system that seeks to combine the strengths of both variational and ensemble methods. Specific objectives for CAPS over the past year include: 1. The development and intercomparison of ensemble-based DA methods for selected cases; 2. A study of the impact of assimilating fast-scan MPAR data on convective storm analysis and prediction; 3. The development and application of a dual-pol radar simulator and the evaluation of microphysics schemes using dual-pol data.

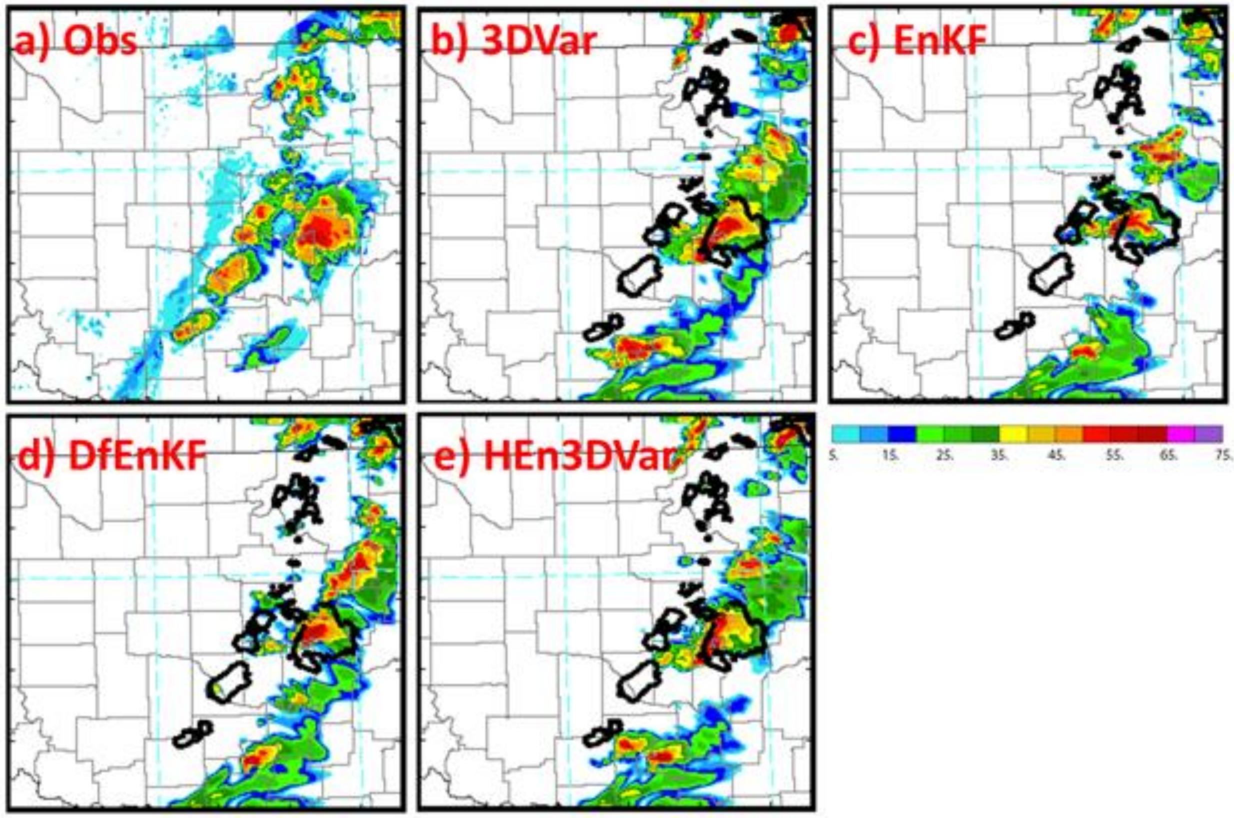
Accomplishments

1. Development and Intercomparison of Ensemble-Based Data Assimilation Methods for Select Cases

Capabilities to directly assimilate radar radial velocity and reflectivity data in the ARPS hybrid ensemble-3DVar (HEn3DVar) data assimilation (DA) system has been developed within the ARPS 3DVar framework, which has been enhanced to properly assimilate reflectivity data. The En3DVar system is coupled with the ARPS EnKF system (hybrid En3DVAR) and is compared with 3DVar, EnKF, and a deterministic forecast EnKF (DfEnKF) for the May 10, 2010 Oklahoma tornadic supercell storms, which were fast moving. Here, DfEnKF uses a single deterministic forecast as the background but perturbations from the regular EnKF system and is therefore algorithm-wise parallel to the pure (one-way-coupling) En3DVar algorithm where a single deterministic forecast is used as the background while ensemble perturbations are obtained from a coupled EnKF system. The model has a 1 km grid spacing and covers central Oklahoma. Four WSR-88D radars (KTLX, KFDR, KINX, and KVNX) and the Oklahoma mesonet observations are assimilated every 5 minutes for an hour. Then One-hour forecasts are initialized from the final analyses using the HEn3DVar, EnKF, DfEnKF, or 3DVar.

By 60 minutes of forecast, all experiments are able to produce the storm that produced the EF3 tornado through the north part of Seminole County (figure below). DfEnKF outperforms EnKF in terms of the spatial coverage and intensity of reflectivity compared to observations. 3DVar and HEn3DVar forecasts are largely similar. However, the hook echo feature is better captured in Hen3DVar with more intense mesocyclone. These still preliminary results indicate that the hybrid En3DVar system appears to be working for

this real data case, and the hybrid DA appears to be advantage over both pure EnKF and 3DVar. Further tuning of the experiments is underway for further improvement.



a) Observed reflectivity mosaic and 60-min forecast reflectivity and wind vector fields at 1 km height, from b) 3DVar, c) EnKF, d) DfEnKF, and e) hybrid En3DVar with 75% weights given to the static and ensemble background error covariances. The region of observed radar reflectivity exceeding 35 dBZ is outlined by a bold black contour.

2. Study on the Impact of Assimilating Fast-Scan MPAR Data on Convective-Storm Analysis and Prediction

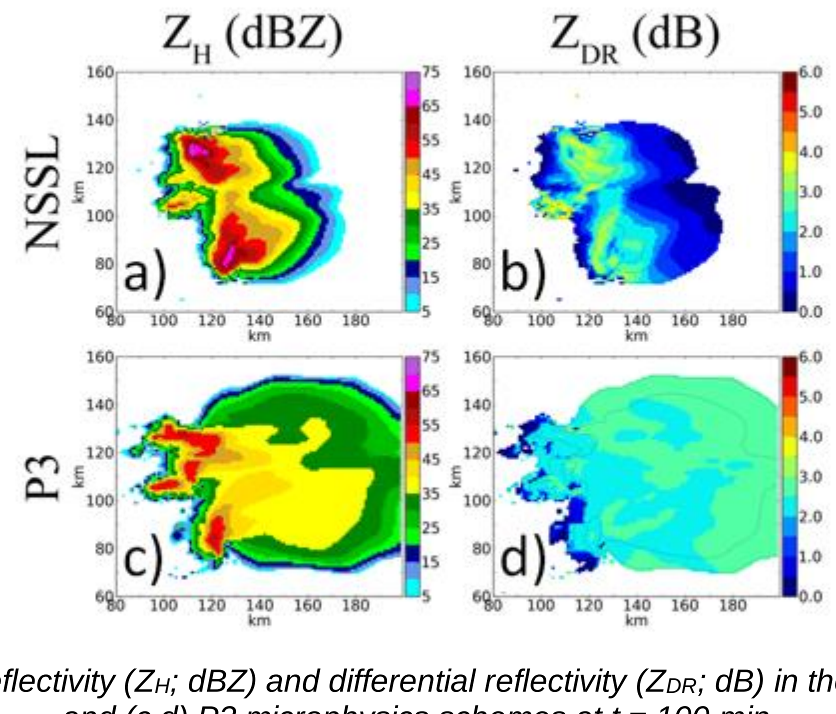
The impact of PAR data on severe weather forecasting was examined through cycled data assimilation and forecast experiments for the 21 May 2011 Ada, Oklahoma, supercell case (Supinie et al. 2017). The experiments use the ARPS 4D ensemble square root filter (4DEnSRF) in a heterogeneous mesoscale environment. Three experiments were compared: one assimilating WSR-88D data (called “WSR-88D”), one assimilating full PAR volumes (called “PAR”), and one assimilating PAR volumes in which tilts have been removed to simulate WSR-88D volumes (called “PAR-reducedtilts”). These data are assimilated over a 45-minute period from 0030 to 0115 UTC 22 May, and 1-hour forecasts are launched every 15 minutes.

With a 30-min assimilation period, the PAR experiment is able to analyze more realistic storm structures, resulting in higher skill scores and higher probabilities of low-level vorticity that align better with the locations of radar-derived rotation compared to the

WSR-88D and PAR-reducedtilts experiments. By the 0115 UTC initialization, the differences between all three experiments are less, suggesting that PAR data are most useful over short assimilation periods. Additionally, the PAR-reducedtilts experiment performs most similarly to the WSR-88D experiment, suggesting the better performance of the PAR experiment is primarily due to the high-temporal resolution PAR observations.

3. Development and Application of Dual-Pol Radar Simulator and Evaluation of Microphysics Schemes Using Dual-Pol Data

The CAPS Polarimetric Radar data Simulator (CAPS-PRS) has been improved to support the predicted particle properties (P3) scheme containing a single ice category that spans a continuous ice spectrum and changes distribution shape based on riming and mixing ratio/number concentration. The updates account for varying particle density depending on the degree of riming, which is also applicable to the National Severe Storms Laboratory (NSSL) scheme that predicts rimed ice bulk density. Improved CAPS-PRS has been applied to an idealized supercell simulation using the P3 and NSSL schemes for their performance evaluation. Compared to the NSSL scheme, the P3 scheme shows the lack of size-sorting at low levels (figure below). Horizontal and vertical cross sections reveal the P3 scheme can simulate midlevel rimed ice size sorting, but produces homogenous rain size. The P3 scheme fails to reproduce the hail signature as very little rimed ice reaches the surface while the NSSL scheme produces large, dry hail at the surface capable of reproducing the Z_{DR} hole. These results were relayed to the P3 authors to guide improvement of the microphysics scheme (e.g., rain size gradients, increased surface rimed ice).



Simulated reflectivity (Z_H; dBZ) and differential reflectivity (Z_{DR}; dB) in the (a,b) NSSL and (c,d) P3 microphysics schemes at t = 100 min.

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CIMMS Task III Project – Mobile Radar Operations to Support VORTEX-SE

Mike Biggerstaff and Gordon Carrie (OU School of Meteorology), and David Bodine (ARRC)

NOAA Technical Lead: Steven Koch (NSSL)

NOAA Strategic Goal 2 – *Weather-Ready Nation – Society is Prepared for and Responds to Weather-Related Events; and*

Funding Type: CIMMS Task III

Objectives

Deploy and operate SMART and RaXPOL radars in support of the VORTEX-SE Spring 2017 field campaign conducted in northern Alabama. A secondary objective was to provide quick-look quality control and to submit the data to the Environmental Observing Laboratory archive.

Accomplishments

The SMART radar was deployed during all operational missions and performed as specified in the proposal. The RaXPOL radar was provided to VORTEX-SE on a non-interfering basis to previously funded projects, as was proposed. The RaXPOL radar deployed on all the missions required to satisfy the terms of the proposal. Data from both radars underwent basic quality control to mitigate power biases in differential radar reflectivity measurements and to ensure proper time and location navigational metadata within the files. Data from both radars was submitted to the Environmental Observing Laboratory mass archive.

SR2 at the Sand Mountain site in northern Alabama during the spring 2017 VORTEX-SE project.

CIMMS Task III Project – Three-Dimensional Profiling of the Severe Weather Environment

Phillip Chilson (OU School of Meteorology), Robert Huck (OU College of Engineering), Andrea L'Afflitto (OU Aerospace and Mechanical Engineering), and Jorge Salazar (ARRC and OU Electrical and Computer Engineering)

NOAA Technical Lead: Steve Koch (NSSL)

NOAA Strategic Goal 2 – *Weather Ready Nation: Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Task III

Objectives

Adapt and evaluate two pairs of multi-rotor VTOL (Vertically Take Off and Landing) copters, to obtain soundings of the atmosphere up to 3,000 ft AGL at two Oklahoma

Mesonet locations, along with transects from a fixed-wing aircraft between the two sites to assess horizontal homogeneity, including in gusty winds.

Accomplishments

The accomplishments of the EPIC (Environmental Profiling and Initiation of Convection) project during the report period can be largely described in terms of hardware development, software development, and the field deployments. We outline those as separate topics

1. Hardware Development

We developed a UAS (unmanned aircraft system) completely in house for this experiment. Initially we tried to find a suitable COTS (commercial off the shelf) platform that we could purchase and then outfit with sensors. After considering several options, we decided to design and build a UAV (unmanned aerial vehicle) which had the needed endurance and range and which could withstand strong (40 kt) winds. The resulting OU CopterSonde is an octo-rotor copter based on a hashtag frame design. See Figure 1. The vehicle can be controlled manually or in autopilot mode. The on-board autopilot is the Ardupilot software running on a Pixhawk. The inertial measurement unit (IMU) and GPS is built into the Pixhawk. Additionally, the system is equipped with differential GPS to improve accuracy of the positioning of the vehicle (2-8 cm) when in flight. The CopterSonde can maintain safe and stable flight even in the event of prop/motor failure. It is anticipated that the CopterSonde will be capable of operating in winds up to 50 knots. The platform is equipped with for temperature and four relative humidity sensors. Pressure data are recorded from barometer on the Pixhawk. Wind is calculated by monitoring the three Euler angles output by the IMU. Three CopterSonde units were built for the project.

2. Software Development

Data from the Pixhawk are transmitted to a ground station using the MAVLINK protocol. Multiple parameters associated with the operation and status of the aircraft are transmitted. The external data from the temperature and humidity sensors are integrated through a specially developed break-out circuit board and then feed into the I2C port of the Pixhawk. These are also transmitted to the ground station through the RF link between the CopterSonde and the ground station. In the current version, after the CopterSonde has landed, a Python script is run which allows a visualization of the recorded data. Examples of output plots for data collected during the EPIC field campaign on May 19 at the Marshall Mesonet site are shown in Figures 2-5.

3. Field Deployments

There were two field deployments as part of EPIC. One was a dry run at the DOE ARM SGP site in late October 2016 and then the actual experiment in May 2017 in upper Oklahoma. The logistical organization of the operations was to have vertical profiles of the atmosphere at one site (DOE ARM SGP) using rotary wing aircraft provided by OU

(CopterSonde) and Meteomatics (Meteodrone) and a similar configuration at another site (Mesonet). The CU TTwistor would fly transects between the two sites. As ground support, the NSSL CLAMPS (Collaborative Lower Atmosphere Mobile Profiling System) and an NSSL mobile mesonet were deployed. See Figure 8. The Meteodrone and CopterSonde collected measurements of the atmospheric temperature, humidity, pressure, and wind with height. The TTwistor measured the same parameters but while flying at a fixed altitude between the sites. CLAMPS sampled the temperature, humidity, and wind with height through the use of a microwave radiometer, an AERI (Atmospheric Emitted Radiance Interferometer), and a scanning Doppler Lidar. Both the CLAMPS and mobile mesonet units launched radiosondes. Deployment of the EPIC assets was directed by the National Weather Service. That is, during a daily weather briefing, it was decided if storms might develop and if so where the EPIC team should deploy. Originally it was planned to use the DOE ARM SGP site as the hub of operations an then choose a transect off that hub corresponding to a Mesonet site. See Figure 9. We were not able to get approval to operate the Meteodrone and CopterSonde at the DOE ARM SGP site on time, so instead we operated from two Mesonet sites. The measurements were largely successful and we are now in a data analysis phase.

Figure 1: The CopterSonde in flight at the DOE ARM SGP site.

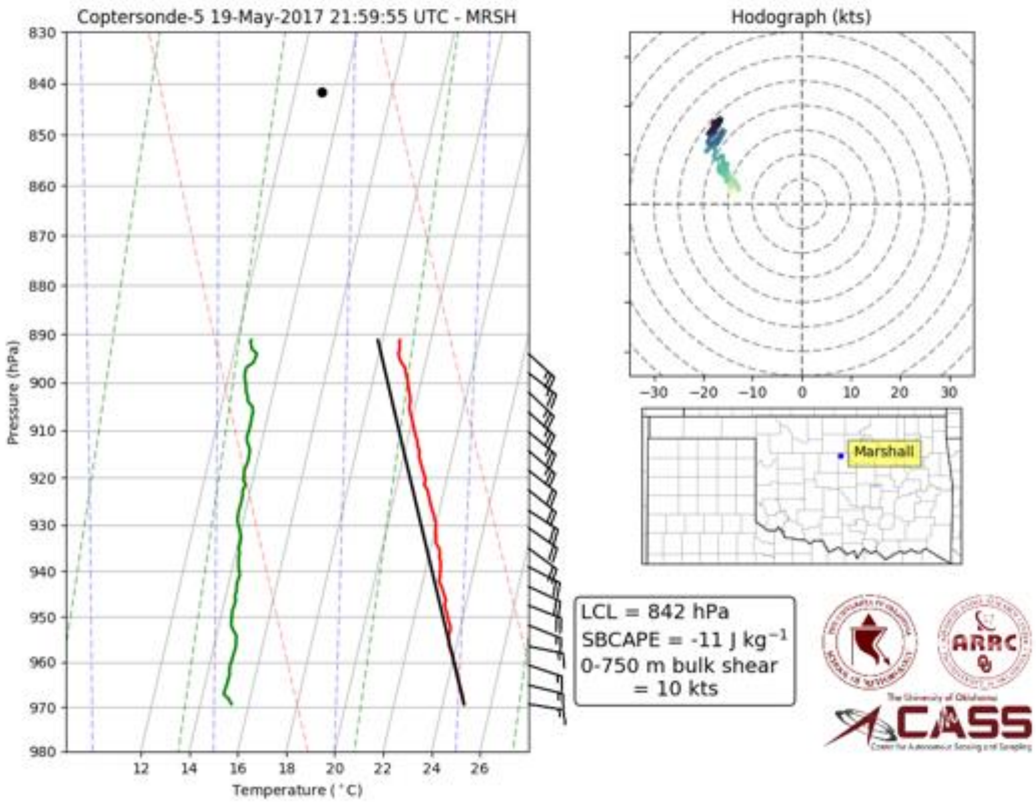


Figure 2: Skew T – log p plot generated for data collected at the Marshall Mesonet site on May 19 during EPIC.

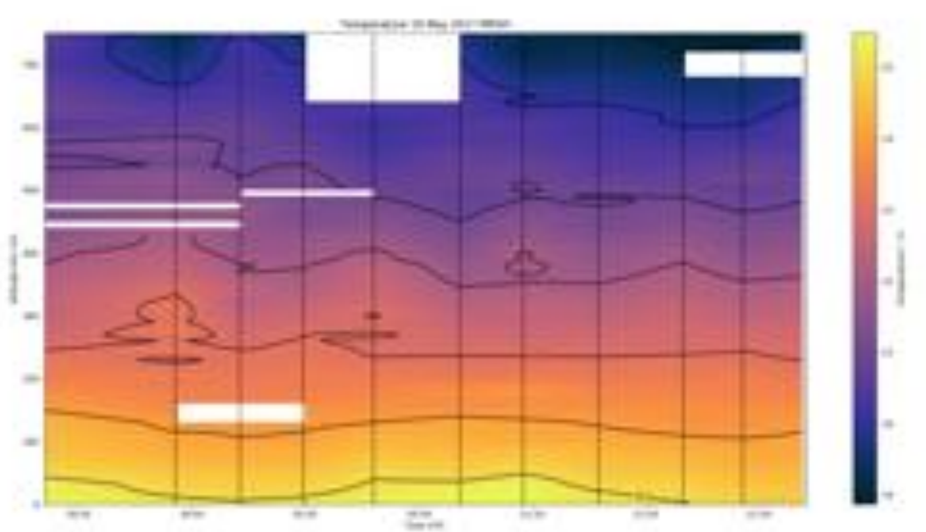


Figure 3: Time height plot of temperature data collected with the CopterSonde at the Marshall Mesonet site on May 19 during EPIC.

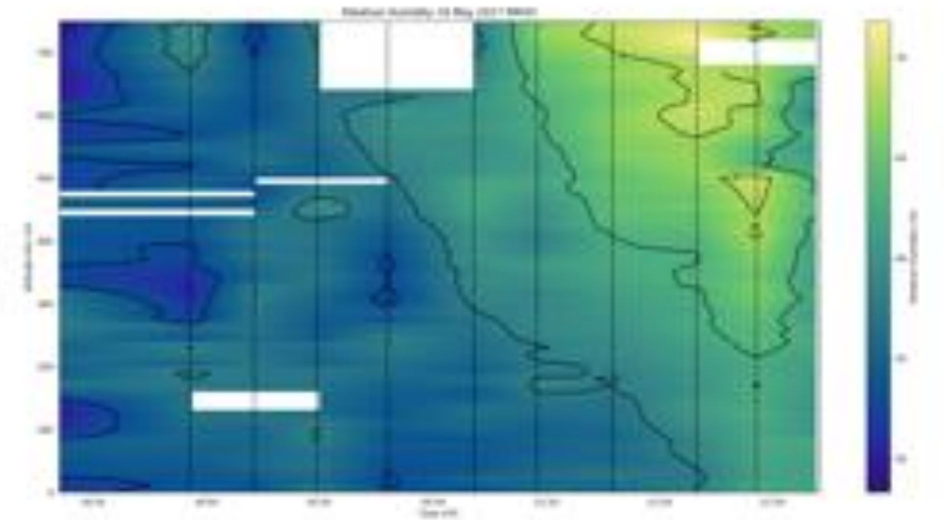


Figure 4: Time height plot of relative humidity data collected with the CopterSonde at the Marshall Mesonet site on May 19 during EPIC.

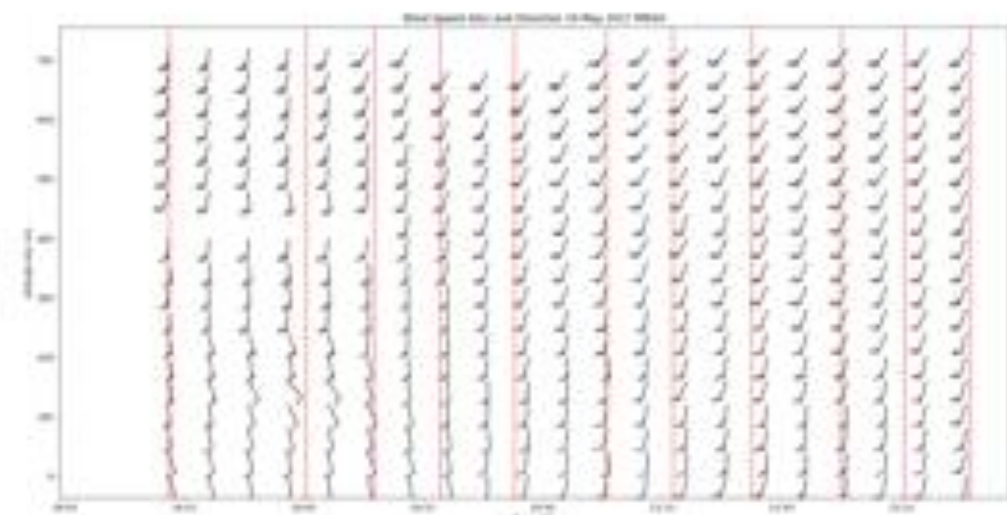


Figure 5: Time height plot of wind data collected with the CopterSonde at the Marshall Mesonet site on May 19 during EPIC.

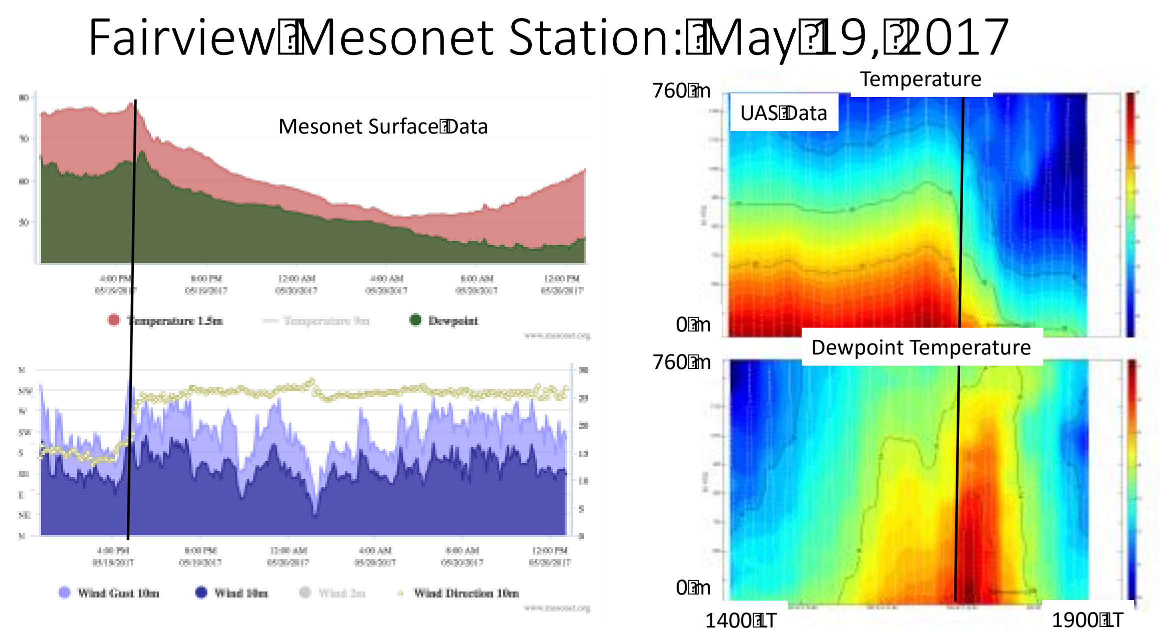


Figure 6: Example of data collected at the Fairview Mesonet site on May 19. Surface data from the Mesonet station together with UAS data indicate a sharp transition in the atmosphere associated with the onset of severe weather. Operations of the UAS were terminated because of the weather risk.

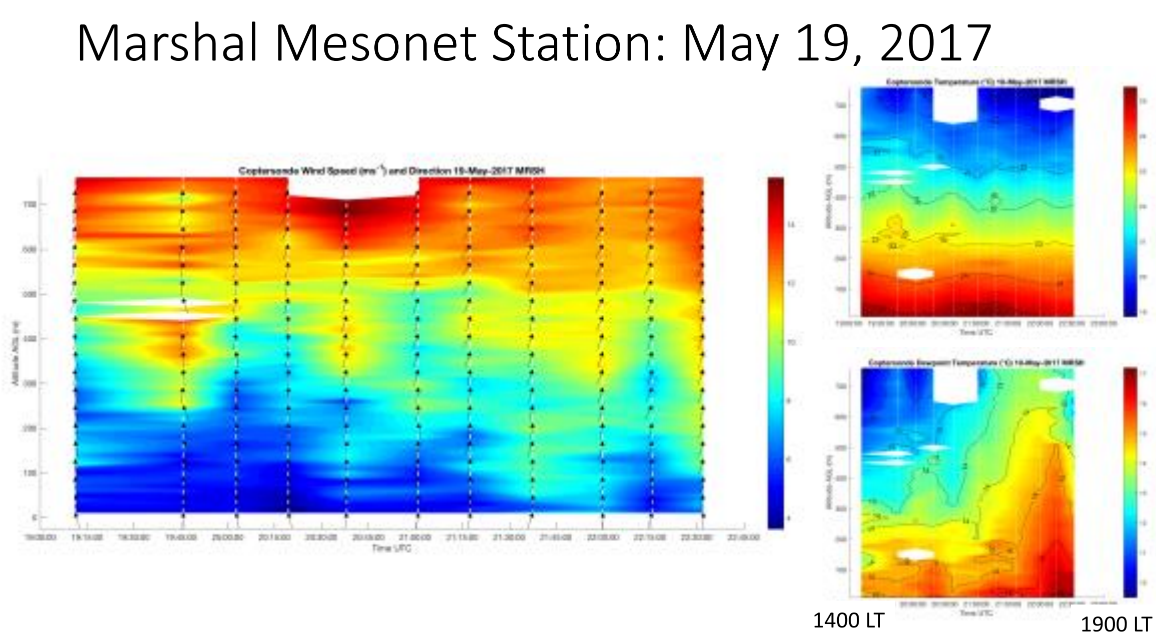


Figure 7: The same as Figure 6 except data were collected at the Marshall site.

Figure 8: Depiction of the instrumentation used in EPIC.

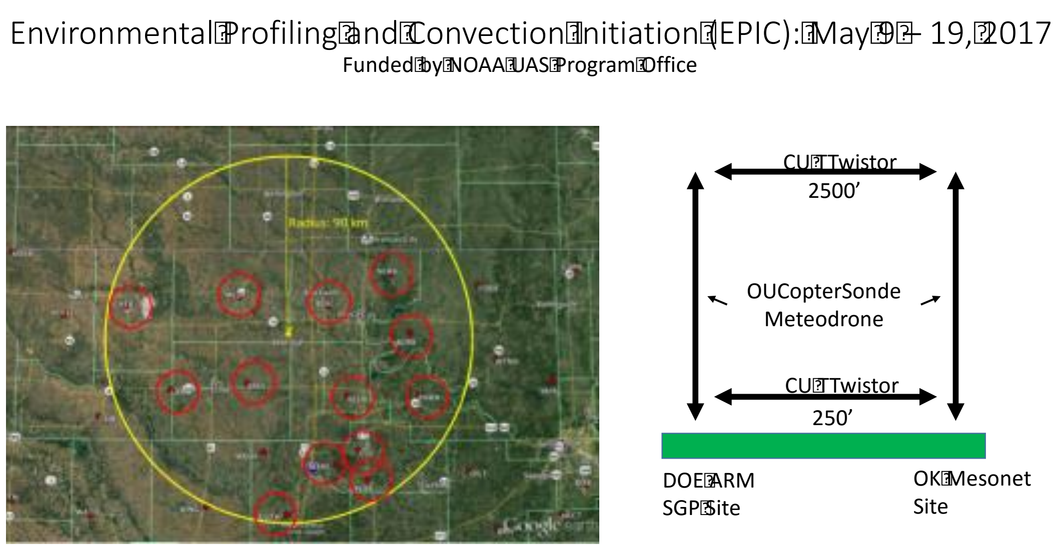


Figure 9: Diagram showing the experimental design for a typical deployment during EPIC.

CIMMS Director's Discretionary Research Funds Special Project – Geo-Fence Radar for Small UAS Weather Observations

Mark Weber (CIMMS Senior Research Scientist affiliated with NSSL), Phillip Chilson (OU Center for Autonomous Sensing and Sampling), Robert Palmer and Mark Yeary (ARRC), Ken Carson (OU Aviation School), and Robert Huck (OU College of Engineering)

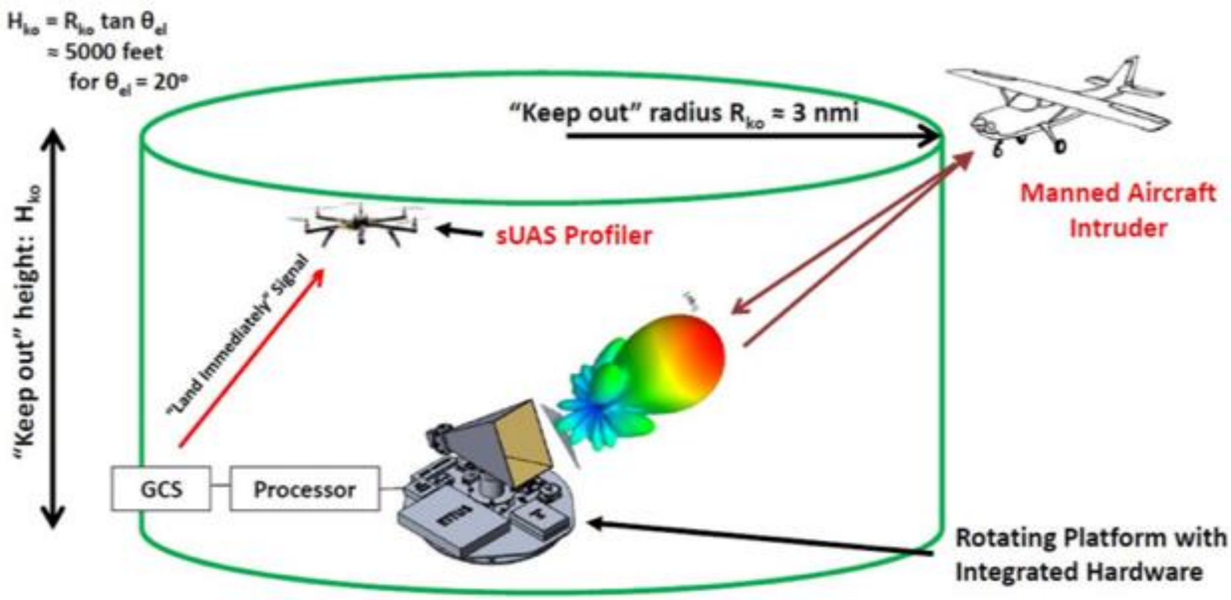
NOAA Strategic Goal 2: Weather Ready Nation – Society is Prepared for and Responds to Weather-Related Events

Funding Type: CIMMS Director's Discretionary Research Fund (DDRF)

Objectives

The University of Oklahoma is developing a "3D-Mesonet" concept which would use small UAS (sUAS) to perform vertical soundings of temperature, moisture and wind from many sites within Oklahoma's operational weather station network. This would provide scientists and forecasters unprecedented, fine-scale information on the structure and evolution of the pre-storm boundary layer and would enable significant, high-impact research at CIMMS and partner organizations. The 3D-Mesonet concept is not viable however unless the Federal Aviation Administration approves routine, unattended sUAS operations on a state-wide basis.

CIMMS DDRF support has enabled development, test and performance analysis of a novel, low- cost radar supporting "detect and avoid" capability necessary for these sUAS operations. Routine operation at many Mesonet sites will require rigorous demonstration that any manned aircraft penetrating a "geo-fence" around the Mesonet site can be detected, enabling the sUAS operation to quickly be terminated. The figure below illustrates the concept of operations.



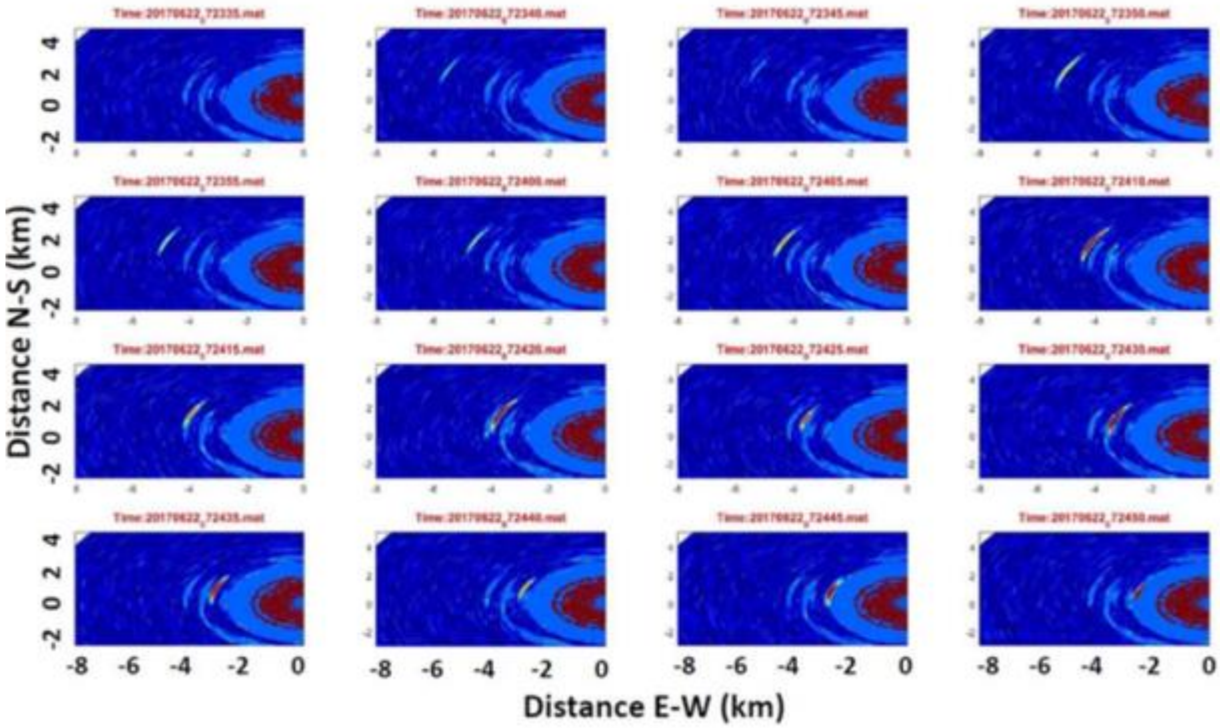
Detect and avoid concept for 3D-Mesonet sUAS operations.

Accomplishments

A set of radar requirements consistent with this concept of operations was developed. These included a high probability of detection to a range of 3 nmi (5 km), coherent operation to support Doppler processing, frequency agility to assure that the radars could adaptively avoid interfering with other RF devices in its operating band, and very low cost (~$10,000 per radar). Faculty, engineers and students at OU's ARRC developed a radar architecture consistent with these requirements, which served as the basis for the prototype system pictured in the figure below. The design exploits a high performance "software defined radio" (AD-9631 RF Transceiver) to perform signal up- and down-conversion, a highly capable, low-cost Gallium Nitride power amplifier and a reconfigurable FPGA supporting waveform generation, radar control and digital signal processing.

Geo-Fence radar prototype, deployed at the OU Radar Innovations Laboratory.

Three flight tests of the prototype radar were performed using a dedicated Seneca Warrior operated by OU's Aviation School. The aircraft flew "racetracks" extending from the ARRC's Radar Innovations Laboratory to a range of approximately 6 nmi, and at altitudes varying from 1000' to 3000' AGL so as to map out the required detection envelope for the radar. The figure below shows an example radar track as the aircraft flew inbound from the northwest at 3000' AGL. The aircraft return becomes visible at a range of 6.3 km and is detected continuously thereafter. Detection performance on all of the other flight legs was similar, demonstrating that the critical design requirement for operating range against a small aircraft target was realized.



Geo-Fence radar for inbound Seneca Warrior track on 22 June 2017. Aircraft is at 3000' AGL. Time is marked at the top of each sweep, and runs from left to right, then top to bottom.

Using the radar design data and flight test results developed during this project, we successfully applied for a $300,000 Oklahoma Center for Advancement of Science and Technology (OCAST) grant that will allow us to refine and commercialize the Geo-Fence radar concept. These data will also be critical in ongoing interactions with the Federal Aviation Administration to certify technologies and procedures necessary for safe operation of a future 3D-Mesonet.

Theme 4 – Impacts of Climate Change Related to Extreme Weather Events

No research was performed under this cooperative agreement within this research theme during FY2017. Please see the FY 2017 report for work performed under the previous cooperative agreement.

Theme 5 – Societal and Socioeconomic Impacts of High Impact Weather Systems

NSSL Project 9 – Evaluating the Impact of New Technologies, Data, and Information in the Operational Forecast Environment

NOAA Technical Lead: Steven Koch (NSSL)

NOAA Strategic Goal 2 – *Weather-Ready Nation – Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Director's Discretionary Research Fund

Development of a New Prototype Particle Imager

Erik Rasmussen (CIMMS at NSSL) and Sean Waugh (NSSL)

Objectives

This objective of this project is to develop a new prototype particle imager that could be adapted for a variety of precipitation and deployment methods. The imager will consist of multiple high-resolution, fast imaging cameras focused on a common zone in the center of the camera array. The cameras will be placed so that imaging of particles formed through breakup owing to collisions with the imager will be minimized. Associated software will measure particle size and shape, and produce three-dimensional high-resolution depictions of the imaged particles. This information is very important for both understanding and calibrating precipitation distributions inferred from dual-polarization radar, as well as improving numerical prediction models.

Accomplishments

Sean Waugh performed extensive research and testing to determine the optimal camera characteristics and currently available COTS cameras. This work also has improved the overall design concept of the imager.

CIMMS Task III Project – Coping with Drought: Building Resilience to Drought

Mark Shafer (OCS at OU), Kirsten Lackstrom (CISA – University of South Carolina), Kathie Dello (CIRC – Oregon State University), and Michael Wolfinbarger (Weather Decision Technologies, Inc.)

NOAA Technical Lead: Claudia Nierenberg (NOAA CPO)

NOAA Strategic Goal 1 – *Climate Adaptation and Mitigation: An Informed Society Anticipating and Responding to Climate and its Impacts*

Funding Type: CIMMS Task III

Objectives
This project advances drought coordination at multiple levels through four themes: (1) Coping with Drought RISA Team Meeting; (2) Integrating Drought Condition Reporting into the Drought Monitor; (3) Creating an Inventory of Drought-Related Research; and (4) Developing a Ten-Year Vision of Drought Resilience in the Southern Plains. The RISA Team meeting brings together RISA teams that receive Coping with Drought funding via NIDIS to compare their efforts, assess methodologies used to learn about decision processes related to drought, and coordinate activities within NIDIS and the Drought Early Warning Systems. Integrating Drought Condition Reporting completes development of a mobile drought information and reporting app (developed by WDT) and connects reports from users to the Drought Impacts Reporter at the National Drought Mitigation Center. The Inventory of drought-related research builds a database of Federal grant opportunities and publications for inclusion on the U.S. Drought Portal (http://www.drought.gov). The Ten-Year Vision convenes a group of scientists and stakeholders to identify long-term solutions to the challenges of preparing, monitoring, and responding to drought in the Southern Plains.

Accomplishments
Pertaining to each of the four themes:

Coping with Drought RISA Team Meeting. A meeting with six RISA teams (CIRC, CISA, CLIMAS, CNAP, SCIPP, and WWA), the NIDIS Program Office, and NOAA's Climate Program Office occurred 14-15 February 2017 at the NWC. Discussions included the history of the RISA and NIDIS programs, program needs, expertise among the teams and programs, and possible future funding scenarios. A summary report was provided to the RISA Program office and NIDIS.

Integrating Drought Condition Reporting into the Drought Monitor. This task is on hold until a mobile phone drought app is completed and available for beta testing (fall 2017).

Creating an Inventory of Drought-Related Research. The project, led by Aimee Franklin (University of Oklahoma Department of Political Science), identified keywords used in drought-related research, searched drought.gov to identify past agency calls for proposals that included those keywords, identified drought-related publications, and identified non-peer-reviewed reports related to drought. The project team built databases of grant opportunities and publications that will be integrated into the research tab on the NIDIS Drought Portal. Initial analysis of the data identified inconsistencies among agencies and years in name an numbering format, identified organizations that offer drought-related funding but may not be well-connected to NIDIS, and an initial analysis of the links between the calls for proposals and production of peer-reviewed articles or reports.

Developing a Ten-Year Vision of Drought Resilience in the Southern Plains: A panel of experts (stakeholders and scientists) has been assembled, but not yet met. The panel is charged with examining: impacts of drought sector-by-sector; how long

after a drought begins it takes before problems emerge in each sector; monitoring networks and available indices; communication practices; resources and practices available to lessen drought impacts; and resources and practices to lessen risk on a long-term basis.

Analysis of the relationship between funding, research, and instrumental use of drought-related research funded by Federal agencies and programs. The project hypothesizes that calls for proposals focuses research around topics, those funded projects are conducted over several years, and research is applied by stakeholders to improve their management of and preparedness for drought.

CIMMS Task III Project – Establishing a Baseline: Public Reception, Understanding, and Responses to Severe Weather Forecasts and Warnings in the Contiguous United States

Carol Silva, Joseph Ripberger, and Hank Jenkins-Smith (OU Center for Risk & Crisis Management – CRCM)

NOAA Technical Lead: Lans Rothfusz (NSSL)

NOAA Strategic Goal 2 – *Weather Ready Nation: Society is Prepared for and Responds to Weather-Related Events*

Funding Type: CIMMS Task III

Objectives

Identifying valid and reliable indicators of social conditions (such as forecast and warning reception, understanding, and response); creating baseline measures of these indicators under the current forecast and warning system; and designing a protocol that will allow the NWS to track these indicators over time and space so that program managers can empirically detect changes that occur as, when, and where the NWS implements new policies.

Accomplishments

Improvements to forecasts and warnings are not always sufficient to generate this outcome. Rather, there are many social conditions that must be met. For example, members of the public must receive, understand, and respond to the forecasts and warnings that the NWS issues. If one or more of these conditions are not met, improvements to forecast and warning technology will not necessarily advance the mission of the NWS. As such, we recommend that the NWS consider these and other social conditions when measuring performance before, during, and after policy changes. Accomplishing this task will require at least three things:

1. Identifying valid and reliable indicators of social conditions (such as forecast and warning reception, understanding, and response);
2. Creating baseline measures of these indicators under the current forecast and warning system;
3. Designing a protocol that will allow the NWS to track these indicators over time and space so that program managers can empirically detect changes that occur as, when, and where the NWS implements new policies.

In Year 1 of this project (7/1/15-9/30/16), the University of Oklahoma Center for Risk & Crisis Management (CRCM), began working on item one (valid and reliable indicators) by systematically reviewing previous research on forecast and warning reception, understanding, and response. In this review, we identified indicators that currently exist in the literature and gaps in our understanding. Following this review, we used the Oklahoma M-SISNet (Jenkins-Smith et al. 2017), a panel survey of approximately 2,000

residents of Oklahoma, to validate indicators of new concepts that are not yet addressed in the literature.

In Year 2 of the project (10/1/16-9/30/17), CRCM designed and fielded a nationwide survey on severe weather in the United States. The University of Oklahoma provided funding for all data collection. The Severe Weather and Society Survey (WX17) was fielded June 20-22, 2017 using an online questionnaire that was completed by 2,009 U.S. adults (age 18+) that were recruited from an Internet panel that matches the characteristics of the U.S. population as estimated in the U.S. Census. Pursuant to item two (above), WX17 was designed to establish baseline measures of the extent to which U.S. adults receive, understand, and respond to severe weather forecasts and warnings under the current watch, warning, and advisory (WWA) system. In addition to this set of baseline measures, WX17 measured other social and behavioral factors that the NWS might consider when evaluating performance, including public preferences about tradeoffs during the forecast process (i.e., lead time vs. accuracy/precision of warnings), trust in the NWS (relative to other groups), hazard risk literacy, the relative importance of probability and intensity in risk characterization, and the value of geographically specific and continuous weather warnings, such as those envisioned by the NSSL FACETs framework.

Results from this research were highlighted in conference proceedings, posters, and presentations, and upcoming manuscripts.

Public Affairs and Outreach

NOAA Partners Communications, Public Affairs, and Outreach

NOAA Technical Lead: Keli Pirtle (NOAA Public Affairs)

NOAA Engagement Enterprise – *An Engaged and Educated Public with an Improved Capacity to Make Scientifically Informed Environmental Decisions*

Funding Type: CIMMS Task II

Objectives
Communicate CIMMS and NSSL research and news to OU, OAR, NOAA, and Department of Commerce leadership, the U.S. Congress, decision makers, partners, collaborators, and the public.

Accomplishments
1. Data Calls and Monthly Updates – Emily Summars (CIMMS at NSSL)

- Report significant papers: Alert NOAA leadership to published papers determined to be significant by NSSL and CIMMS leadership, add such papers to the OAR Weekly Report and publish in OAR Hot Items. Reports include a summary of each significant paper.
    - CIMMS reported **54** significant papers in FY2017.
- Provide report numbers for Quarterly Education performance taskers to NSSL leadership and CIMMS leadership as needed.
- Provide monthly social media updates, story progress updates and project updates via email and the weekly NSSL Managers Meetings.

2. NOAA and OAR Communications – Emily Summars (CIMMS at NSSL)

- OAR Hot Items: Describe new research, activities and publications. Hot items are posted on the OAR Hub, where the OAR Communications team reviews and chooses significant topics to be added in the Department of Commerce Secretary's Weekly Report. **Twelve** Hot Items were submitted on behalf of NSSL and CIMMS in FY2017, including several topics like VORTEX-SE and CLEAN-AP.
    - Department of Commerce Secretary's Weekly Report: Significant OAR Hot Items are condensed into a few sentences to be included into the Department of Commerce Secretary's Weekly Report. Work with HQ to ensure the accuracy of these items, add details and other items as requested by OAR leadership. CIMMS items featured in the report include publications, VORTEX-SE, participation in EPIC and RiVorS.

3. Research Projects – James Murnan (ACE) and Emily Summars (CIMMS at NSSL)

- Accompany researchers to video, conduct interviews, and take photos during research projects. Examples included VORTEX-SE, EPIC and Hazardous

Weather Testbed experiments. Provide social media updates while in the field to provide an "in-that-moment" view for followers. The final result from time in the field includes story(s), video, social media updates, and/or a Flickr album.

4. Project Fact Sheets – Emily Summars (CIMMS at NSSL)

- Fact Sheets are 1-2 page handouts on NSSL/CIMMS projects used to give visitors and guests a "take-away" message. **Seven** Fact Sheets involving CIMMS were designed, written, edited and updated in FY2017, including fact sheets for VORTEX-SE media day, and Congressional fact sheets for MRMS, MPAR and more.

5. CIMMS on Social Media – Emily Summars (CIMMS at NSSL)

- CIMMS's Facebook and Twitter accounts are growing in popularity. New content is published daily based on monthly or daily themes. Partner posts are shared as appropriate. Project photos from researchers, days in the field and media days are shared on NSSL's also has Flickr, Instagram and Pinterest accounts. Updated Facebook and Twitter photos and headers as appropriate. Monitor comments and remove comments using inappropriate language or targeting other individuals.
    - **CIMMS Facebook "likes"**
        - **2017: 780**
        - **2016: 613**
        - **2015: 375**
    - **CIMMS Twitter "follows"**
        - **2017: 642**
        - **2016: 512**
        - **2015: 282**

6. CIMMS Outreach Emails – Emily Summars (CIMMS at NSSL)

- The public submits questions to CIMMS via the CIMMS Outreach email account. The account existed before FY2017 but was added to OU CIMMS website and social media in FY2017.
- Staff outreach:
    - Send reminders about NSSL and OU CIMMS internal Gab at the Lab.
    - Work closely with the College of Atmospheric and Geographic Sciences to ensure all students, faculty and staff are recognized properly in CIMMS related publications and releases.
    - Share stories and social media posts involving students with the College to ensure collaborative efforts.

7. CIMMS Website – Vicki Farmer (ACE) and Emily Summars (CIMMS at NSSL)

- Review, update and post content to the CIMMS website at least once a week.
- Redesign certain products to create a cohesive brand.
- Track awards, accomplishments and publications then post items considered of interest.

8. Back-up NOAA Weather Partners Public Affairs – Keli Pirtle (NOAA Weather Partners) and Emily Summars (CIMMS at NSSL)

- Help Keli Pirtle and other NOAA partners field media calls pertaining to CIMMS.
- Provide additional information on projects involving CIMMS researchers.
- Ensure CIMMS researchers are mentioned properly in news and other media articles.

9. Public Education and Outreach – Patrick Hyland (OU College of Atmospheric and Geographic Sciences)

- Lead tour program of the National Weather Center, including NOAA.
- Plan and organize National Weather Festival activities.
- Facilitate educational outreach opportunities.
- Collaborate with NOAA and CIMMS public relations office on requests that require crossover into both the university and NOAA.

CIMMS Staff at WDTD Outreach

Alyssa Bates, Jill Hardy, Austin Harris, Eric Jacobsen, Dale Morris, Chris Spannagle, Phillip Ware, Andrew Wood, and Alex Zwink (CIMMS at WDTD), and Michael Bowlan (CIMMS at SPC)

CIMMS staff at WDTD regularly engaged in various outreach activities during the past year. Most of the activities involved partnerships with other organizations in the National Weather Center, while others were outside of the building supporting the local community. These outreach activities included:

- Working support “shifts” at the NWS Norman Weather Forecast Office (WFO) during severe weather events;
- Planning and participating in the hands-on “Issue Your Own Warning” activity at the National Weather Festival;
- Volunteering with other National Weather Center organizations during the Norman United Way Day of Caring;
- Organizing and instructing four mini-workshops for School of Meteorology students on warning fundamentals;
- Volunteering with the Junior Achievement Job Shadowing Program;
- Leading a hands-on lab session on issuing weather warnings to high school students for Oklahoma Mesonet’s Regents Camp; and
- Giving career day talks about meteorology to elementary school students in Norman and Oklahoma City.

CIMMS instructor Chris Spannagle showing Regents Camp participants how National Weather Service forecasters issue severe weather warnings.

Appendix A

AWARDS AND HONORS

The following awards or other notable achievements occurred during the fiscal year. CIMMS staff (present and past) in **bold**:

Presidential Early Career Award for Scientists and Engineers (PECASE), 2016: **Corey Potvin**

AMS 2016 17th Conference on Mountain Meteorology "Service to the Society" Award: **Heather Reeves**

OU School of Meteorology 2016 Yoshi Sasaki Award for Best M.S. Publication: **Katie Wilson**

National Weather Association 2016 Roderick Scofield Scholarship: **Katie Wilson**

National Weather Association 2016 Larry R. Johnson Special Award: **Travis Smith, Valliappa Lakshmanan, Gregory Stumpf, Kiel Ortega, Kurt Hondl, Karen Cooper, Kristin Calhoun, Darrel Kingfield, Kevin Manross, Robert Toomey, Jeff Brogden, Tiffany Meyer, Kevin Scharfenberg, Tony Reinhart, Brandon Smith, Chris Karstens, Holly Obermeier, Matt Mahalik, Clark Payne, Alyssa Bates, Jill Hardy, Chris Spannagle, Matt Taraldsen, Andy Wood**, James LaDue, Robert Prentice, **Matthew Elliot**

OU College of Atmospheric and Geographic Sciences 2016 Dean's Award for Outstanding Service: **Sebastian Torres**

Named Associate Editor for AMS *Journal of Atmospheric and Oceanic Technology* 2017: **Sebastian Torres**

AMS 2017 7th Conference on Transition of Research to Operations Student Competition Poster Presentation Winners: **Katie Wilson** and **Makenzie Krocak**

AMS 2017 17th Conference on Mesoscale Processes Second Place Oral Presentation Winner: **Hristo Chipilski**

Association for Talent Development's 2017 *One to Watch* Program Honoree: **Megan Taylor**

Named 2017 Emerging Training Leader by *Training* Magazine: **Megan Taylor**

Elected AMS Fellow in 2017: **Alexander Ryzhkov**

Named 2017 OU Student Government Association Outstanding Faculty Member: **Randy Peppler**

Bulletin of the American Meteorological Society Paper of Note: **Randy Peppler**, published in *Weather, Climate, and Society*, April 2017

American Geophysical Union Research Spotlight Article: **Darrel Kingfield**, **Kristin Calhoun**, and Kirsten de Beurs, published in *EOS*, 26 May 2017

Bulletin of the American Meteorological Society Paper of Note: **Darrel Kingfield** and Kirsten de Beurs, published in *Journal of Applied Meteorology and Climatology*, June 2017

Appendix B

PUBLICATION SUMMARY*

	CIMMS Lead Author				NOAA Lead Author				Other Lead Author			
	2009-10	2010-11	2011-12	2012-13	2009-10	2010-11	2011-12	2012-13	2009-10	2010-11	2011-12	2012-13
Peer Reviewed	32	28	31	32	28	32	13	8	40	44	35	45

	CIMMS Lead Author				NOAA Lead Author				Other Lead Author			
	2013-14	2014-15	2015-16	2016-17	2013-14	2014-15	2015-16	2016-17	2013-14	2014-15	2015-16	2016-17
Peer Reviewed	57	60	62	***45***	9	7	5	***5***	44	40	52	***44***

**Publication numbers are approximate. Numbers are slightly lower this year as they are strictly fiscal year.*

Appendix C

PERSONNEL SUMMARY – NOAA FUNDED RESEARCH ONLY

Category	Number	B.S.	M.S.	Ph.D.
Research Scientist	82	2	46	34
Visiting Scientist	2		2	
Postdoctoral Fellow	13			13
Research Support Staff	15	6	9	
Administrative	3	2	1	
Total (>50% support)	**115**	**10**	**58**	**47**
Undergraduate Students	27			
Graduate Students (current degree)	43	14	29	
Employees that receive <50% NOAA Funding (not including students)	**43**	**6**	**14**	**21**
Located at Lab	NSSL-92, WDTD-18, SPC-10, ROC-9, NWSTC-6, OUN-1			
Obtained NOAA employment within the last year	**5**			

Appendix D

COMPILATION OF CIMMS-RELATED PUBLICATION – FY 2017

Publications compiled here were reported for projects funded under Cooperative Agreement NA16OAR4320115.

Peer-Reviewed Journal Articles, Books, and Book Chapters *Published*

July 2016

Karstens, C. D., K. Shourd, D. Speheger, A. Anderson, R. Smith, D. Andra, T. M. Smith, and V. Lakshmanan, 2016: Evaluation of near real-time preliminary tornado damage paths, *Journal of Operational Meteorology,* **4**, 132-141. http://dx.doi.org/10.15191/nwajom.2016.0410.

August 2016

Borowska, L., G. Zhang, and D. S. Zrnic, 2016: Spectral processing for step scanning Phased Array Radars. *IEEE Trans. on Geoscience and Remote Sensing*, **54**, 4534-4543. https://doi.org/10.1109/TGRS.2016.2543724.

Carlin, J., A. Ryzhkov, J. Snyder, and A. Khain, 2016: Hydrometeor mixing ratio retrievals for storm-scale radar data assimilation: Utility of current equations and potential benefits of polarimetry. *Monthly Weather Review,* **144**, 2981-3001. https://doi.org/10.1175/MWR-D-15-0423.1.

Gravelle, C. M., K. J. Runk, K. L. Crandall, and D. W. Snyder, 2016: Forecaster evaluations of high temporal satellite imagery for the GOES-R era at the NWS Operations Proving Ground. *Weather and Forecasting*, **31**, 1157-1177. https://doi.org/10.1175/WAF-D-15-0133.1.

Reeves, H., A. Ryzhkov, and J. Krause, 2016: Discrimination between winter precipitation types based on spectral-bin microphysical modeling. *Journal of Applied Meteorology and Climatology,* **55**, 1747-1761. https://doi.org/10.1175/JAMC-D-16-0044.1.

Xie, X., R. Evaristo, S. Troemel, P. Saavedra, C. Simmer, and A. Ryzhkov, 2016: Radar observation of evaporation and implications for quantitative precipitation and cooling rate estimation. *Journal of Atmospheric and Oceanic Technology*, **33**, 1779-1792. https://doi.org/10.1175/JTECH-D-15-0244.1.

Zhang, G. 2016: *Weather Radar Polarimetry*, CRC Press, 322 pp.

September 2016

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Appendix E

<u>NOAA COMPETITIVE AWARD RECIPIENT REPORTS</u>

<u>and</u>

<u>NOAA HURRICANE SANDY COMPETITIVE AWARD RECIPIENT REPORTS</u>

These reports are presented in the format provided by the respective PIs directly to their NOAA Program Managers. ***They appear in a separate file to this document.***