UNIVERSITY PROFILE

Atmospheric Radar Research Center - ARRC University of Oklahoma, USA

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1. Introduction

The Atmospheric Radar Research Center (ARRC) at the University of Oklahoma (OU) is focused on weather radar research and education. This center is a result of a significant investment by the university to accelerate research and learning in an area of great importance to Oklahoma and to the meteorological community in Norman. The ARRC is comprised of a growing research faculty, comprehensive test facilities, and an established, multidisciplinary education program at both the graduate and undergraduate levels. Faculty members and students from the OU Schools of Meteorology (SoM) and Electrical and Computer Engineering (ECE), and from the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) comprise the ARRC and are actively engaged in collaborative research in pursuit of defining the next generation of weather radar sensors.

The study of the atmosphere using remote sensing techniques cuts across traditional disciplinary boundaries. Therefore, the breadth of research topics investigated within the ARRC is multi-disciplinary by necessity. An artist's depiction of these topics is provided in Figure 1. Weather radar is the centerpiece technology, which focuses the ARRC activities. Close collaborations with NOAA's National Severe Storms Laboratory (NSSL) and Radar Operations Center (ROC) enable the ARRC to participate in a diversity of projects. Ongoing research topics include radar polarimetry, phased array radar, profiling radar, advanced signal processing, retrieval algorithms, clutter mitigation, severe storm observations and detection, quantitative precipitation estimation, and general studies of atmospheric physics.

Members of the ARRC are deeply committed to the underlying theme of interdisciplinary education. ARRC faculty members have developed a rather unique curriculum focused

Figure 1. Illustration of the breadth of research topics represented within the ARRC at the University of Oklahoma. Although quite wide in scope, activities focus on the use of advanced weather radars for studies of the atmosphere.

on weather radar. Section 3 describes the program, which exploits the expertise represented within the SoM and ECE. Meteorology and engineering experts at NSSL and the ROC are often called upon to provide lectures in our formal OU courses. As a result, our students are afforded an enriched educational opportunity in the field of instrumented studies of the atmosphere.

2. People

The multi-disciplinary field of radar meteorology, composed of both the technical aspects of radar design/algorithm development and the observational use of radar data, is an important strategic research area at OU. As such, emphasis has been placed in recent years on developing a critical mass of scientists and engineers who can work synergistically to achieve the goals of the program. The ARRC is continually growing with a current membership of nine faculty members, over 20 graduate students, and several postdoctoral fellows, including engineering, computer, and secretarial support staff. The following is a list of faculty members, who make up the ARRC scientific leadership, along with their academic positions, and general research areas.

- Dr. Michael Biggerstaff, Associate Professor (SoM), polarimetric radars, mobile radars, cloud physics and electrification, hurricanes, severe local storms, storm dynamics
- Dr. Phillip Chilson, Associate Professor (SoM), Adjunct Associate Professor (ECE), atmospheric radar interferometry, upper-atmospheric physics, wind profiler technology, atmospheric dynamics
- Dr. Jerry Crain, Professor (ECE), phased array antennas and radar, radomes, microwave antennas, and electro-magnetic systems
- Dr. Robert Palmer, ARRC Director, Professor (SoM), Adjunct Professor (ECE), atmospheric radar signal/array processing, imaging (phased array) radar design, radar interferometry, clutter mitigation
- Dr. Sebastian Torres, Adjunct Assistant Professor (ECE), radar signal processing, design of embedded DSP systems
- Dr. Mark Yeary, Assistant Professor (ECE), radar signal processing, real-time hardware development, next-generation digital receiver design, and radar tracking algorithm development
- Dr. Tian-You Yu, Assistant Professor (ECE), Adjunct Assistant Professor (SoM), Radar signal and array processing, weather radar interferometry, knowledge-based algorithms for detection of severe weather
- Dr. Guifu Zhang, Associate Professor (SoM), Adjunct Associate Professor (ECE), remote sensing theory/technology/application, weather radar polarimetry and interferometry
- Dr. Yan Zhang, Assistant Professor (ECE), intelligent radio and radar sensing, RF-microwave system and instrumentation, random-noise radar, real-time system implementation on FPGA and DSP

As a unique feature of this group, many of the ARRC faculty members in both ECE and SoM hold courtesy appointments in the partner department. These appointments help to facilitate interdisciplinary advising and teaching, and have been made possible through the cooperation of the department-level administrators and other OU entities, such as the Graduate College, which strongly encourages interdisciplinary endeavors.

It should be emphasized that the ARRC has several joint projects with the NOAA laboratories in Norman, many of which are facilitated and administered by CIMMS. NSSL has a significant research program in weather radar and for decades has brought many important radar innovations to the meteorology community. Currently, NSSL operates two S-band weather radar systems - the polarimetric KOUN radar and the Phased Array Radar (PAR), which is the centerpiece of the National Weather Radar Testbed (NWRT). In addition, NSSL is a partner with OU, Texas A&M, and Texas Tech Universities, on the development and operation of two C-band mobile radars, which are appropriately named the Shared Mobile Atmospheric Research & Teaching Radars (SMART-R). NSSL is also working with OU on the development of a mobile X-band dual-polarimetric radar that will be completed this summer. The ROC is located in Norman and is an integral component of NOAA's National Weather Service (NWS) network of WSR-88D weather radars. Its mission is the development, maintenance, and operation of the entire network. In addition to numerous other scientific partners across the country and around the world, members of the ARRC have developed mutually beneficial collaborations with both NSSL and the ROC. Many of the major projects within the ARRC would not be possible without this close relationship.

The ARRC is located on the Research Campus of OU in the recently completed 244,00-square-foot National Weather Center (NWC) building shown in Figure 2. This unique facility brings together numerous OU units, including the SoM and CIMMS, with several NOAA and other government organizations. For example, the weather radar group of NSSL is located on the same floor as the ARRC and is in close proximity to the Applications Branch of the ROC. The NWC building has been instrumental in facilitating the collaboration between the ARRC and NOAA.

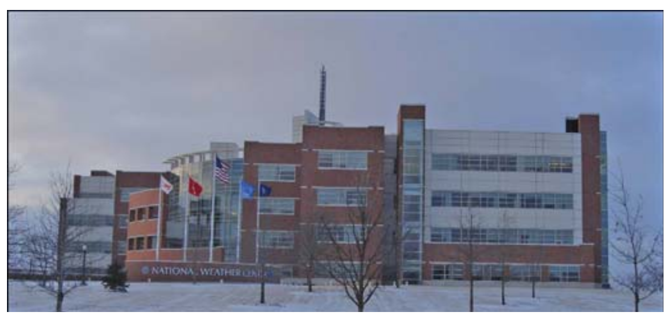

Figure 2. Photograph of the National Weather Center building located on the campus of the University of Oklahoma. This state-of-the-art facility houses the several university and government entities, including the Atmospheric Radar Research Center – ARRC.

3. Education

One of the fundamental goals of the ARRC is providing our students with a comprehensive and challenging education in the area of radar meteorology, which emphasizes both the engineering and meteorological aspects of the field. The following provides a brief description of the over-arching goals of our educational program and more specific information on course offerings.

3.1 General Philosophy and Goals

We achieve our educational goals, in part, by the creation and continual maintenance of a synergistic curriculum that synthesizes the complementary disciplines of meteorology and electrical/computing engineering. As an integral component of the Weather Radar and Instrumentation Curriculum, an innovative and coherent sequence of radar-related courses has been developed which serves both our undergraduate and graduate educational goals. The undergraduate phase of the program is the ideal time to excite students about pursuing graduate studies in the general area of instrumented observations of the atmosphere and in particular weather radar. This novel curriculum is not independent of the more traditional curricula of the two disciplines, but rather forms an important and integral component of them.

Given the importance of weather radar for many observational studies of atmospheric phenomena, it is essential to include a significant hands-on experience for the students. Our curriculum provides a complete theoretical framework with which to understand weather radar theory while also providing access to local weather radar systems. We have developed laboratory modules for many of the radar courses using the SMART radars, the PAR, and the KOUN polarimetric Doppler radar. Experimental design, operation, data analysis, and interpretation are emphasized. It should be noted that the educational activities, within the ARRC, have been partially supported by the National Science Foundation's Division of Undergraduate Education through its Course, Curriculum, and Laboratory Innovation (CCLI) program.

With the goal of facilitating interdisciplinary participation, the courses that comprise this curriculum are generally cross-listed between ECE and SoM. By doing so, the standard requirements of each department are satisfied while allowing students the opportunity to participate in this program. Many of our radar courses could be considered difficult, even within ones own discipline. When taught by a faculty member from another department or when the emphasis is on an unfamiliar discipline, it is often difficult to fully engage in the course. As a conscious design decision in our courses, every effort is made to review necessary material during class with the goal of encouraging educational diversity among the students. Our faculty consists of scientists and engineers who have engaged in interdisciplinary research and education for years and are fully aware of the challenges of such endeavors. More importantly, we are keenly aware of the benefits of seamlessly integrating the disciplines and have organized this unique curriculum with this in mind.

3.2 Course Development Effort

The following figure provides a summary of courses, which make up the Weather Radar and Instrumentation Curriculum at OU. As can be seen, the courses span both the undergraduate and graduate curricula. Many of the courses are new and others have been substantially modified. The specific topics for each course, and the continuity between courses, were compiled from the input of faculty members and scientists from OU, and other local interested groups. As mentioned earlier and with few exceptions, courses are cross-listed between meteorology and electrical/computing engineering. As the program develops and the research field evolves, it is anticipated that new courses may be added and others removed or significantly modified. Such changes are necessary, encouraged, and specifically designed into the administration of the curriculum.

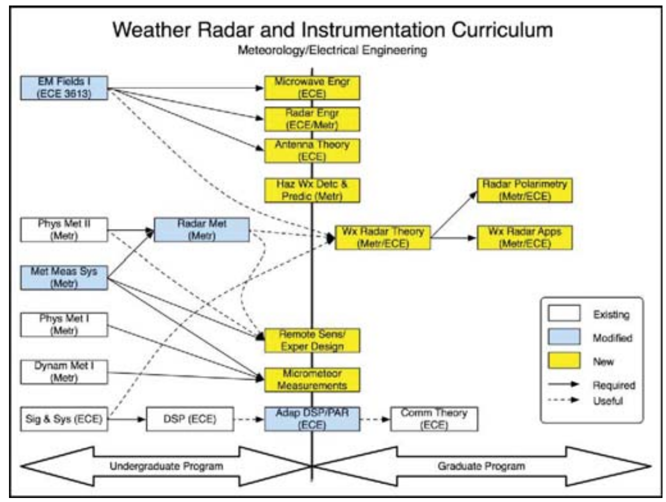

Figure 3. Weather Radar and Instrumentation Curriculum at the University of Oklahoma. The undergraduate and graduate courses are placed to the left and right of the figure, respectively. Solid and dashed arrows denote required and recommended prerequisite courses. Emphasis is placed on interdisciplinary participation and, as a result, significant class time is devoted to background material.

4. Research

Designed synergistically with its educational program, the ARRC's research activities are broad and represent the interdisciplinary nature of the group. The following provides only a brief outline of some of the topics being investigated within the ARRC.

4.1 Radar System Design

The focus of the radar system design effort within the ARRC is to develop customized radar technologies hand-in-hand with the ARRC scientists and engineers, who process and interpret the radar data. By leveraging this interdisciplinary approach, the next-generation of remote sensing systems can be developed with the ultimate goal of improved forecasting, hazardous weather prediction, and convective storm tracking, for example. Supporting these efforts is the ARRC's Radar Innovations Laboratory (RIL), which is depicted in the backdrop of Figure 4. The RIL is functionally dedicated to support RF engineering, customized embedded signal processing systems, and development of hardware solutions for synergistic instrumentation, microphysics experiments, scattering studies, and intelligent processing for scientific discovery. This 4000+ sq. ft. laboratory is located on OU's research campus, near the National Weather Center. Thus, the RIL and its partners are in a position to provide end-to-end radar design, fabrication, and data collection/analysis. The RIL is an interdisciplinary, shared laboratory facility that is designed to be a focal point for partnerships between federal, university, and private enterprise in radar related research, development, manufacturing, training, maintenance, and support.

Figure 4. The ARRC's new Radar Innovations Laboratory is being used to facilitate the design of customized hardware to support the complete cycle of data collection through analysis.

Faculty members within the ARRC are currently applying advanced radar technologies to weather-related hazard monitoring. One aspect of this research is an indoor experimentation facility for hydrometeor scattering characterization under controlled environmental conditions. This unique facility is located within the RIL and is called the Electromagnetics-Microphysics Laboratory (EML). Following these advanced theoretical and experimental studies of wave scattering and propagation, traditional design techniques are used to develop reliable radar systems. One unique system currently under development uses modular receiving elements based on reconfigurable arrays of patch antennas. As analog-to-digital converters become faster, this will allow digital circuits to replace many analog circuit functions. This advancement will provide many additional degrees of freedom to radar processing and allow innovative software-defined-radio techniques to influence the design of digital receivers that follow these antennas. The combination of high-performance computing and distributed sensing provide new tools for researchers to observe the natural world at a fidelity that could only be imagined a few years ago. Activities in the RIL and EML are focused on uniting advanced digital hardware and software to yield computationally intelligent systems for the next-generation of atmospheric remote sensing.

4.2 Phased Array Radar

The nation's first phased array radar deployed for the sole purpose of weather observations is located in Norman, Oklahoma (see left panel of Figure 5). The PAR is an S-band Doppler weather radar recently developed by a government/university/industry consortium consisting of NSSL, Lockheed Martin Corporation, ROC, Office of Naval Research, FAA, BCI, OU, and the other government and private entities. It is envisioned that this prototype radar will serve as a testbed for studies of the feasibility of multi-mission capability, which would provide better utilization of radar resources for weather surveillance, aviation control and target detection/tracking. Collaborating with NSSL's engineers and scientists, ARRC members have been actively working on optimizing scanning strategies, developing and implementing radar interferometry, and advancing radar tracking and imaging techniques, for example.

The PAR has pulse-to-pulse beam steering capability that allows accurate measurements in a shorter dwell time than with a mechanically rotating dish. A novel scanning strategy termed beam multiplexing (BMX) was recently developed and implemented on the PAR with the goal of providing high quality data with fast update times through the collection of independent samples while maximizing the use of radar resources. As a result, the radar beam is steered agilely from one location to another as shown in Figure 5b. Recent experimental results from the PAR indicate that BMX can improve the data update time by a factor of 2 to 4, while maintaining the data accuracy of a mechanically rotating dish. These results are consistent with theoretical projected values. Various BMX-based scanning strategies are currently under development and it is envisioned that BMX data will soon be assimilated into numerical models to determine optimal scan strategies for improved weather forecasts.

The PAR uses an antenna from the AN/SPY1-A radar of the Navy's Aegis system, which uses a phase-comparison monopulse system. This system provides signals of the sum, azimuth difference, and elevation difference channels as shown in Figure 5c. With access to both the sum and difference channels, the monopulse tracking capability will soon be activated, allowing the implementation of advanced tracking algorithms, such as Kalman and particle filtering techniques. In addition to tracking, the sum and difference signals can be used to form the signals from the left and right, and upper and lower, sides of the antenna, allowing measurements of angular shear, and turbulence along the beam, and within the radar's resolution volume using Spaced Antenna Interferometry (SAI) shown in Figure 5d. As scatterers move across the beams, there is a time delay between the two received signals, which is used to determine the crossbeam wind. The SAI technique is being implemented on the PAR via a high-speed RF switch, which is used to receive the signals alternatively between the sum and difference antenna ports. A wave scattering theory has been formulated for weather radar interferometry to retrieve crossbeam wind in the presence of shear and turbulence. It is shown that SAI measures an apparent crossbeam wind and can separate angular shear and turbulence.

The PAR also includes six sidelobe cancellation elements (two are depicted in Figure 5d) that allow the application of adaptive clutter mitigation schemes. Using both the PAR and advanced radar simulations, the ARRC is actively involved in the development of novel array processing schemes, many of which are designed to mitigate both stationary and non-stationary clutter. In addition, these processing methods have been shown to provide enhanced spatial resolution over what is expected from traditional radar theory. Many of these concepts are being actively pursued for implementation on future phased array systems and hold promise to revolutionize remote sensing of the atmosphere.

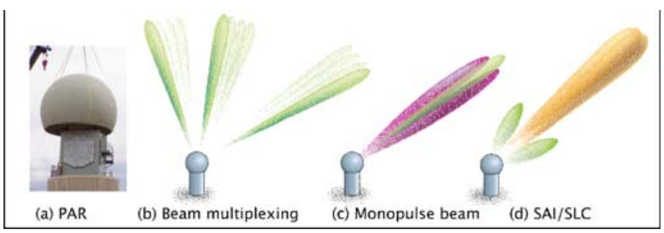

Figure 5. The NWRT phased array radar, (a) photograph of the installation of the radomes of the PAR, (b) sketch of BMX principle, (c) sketch of monopulse beams for target tracking, and (d) sketch of SAI beams for wind measurement along with two sidelobe canceling elements.

4.3 Radar Signal Processing

ARRC members are actively engaged with the development and implementation of novel signal processing techniques to enhance radar performance and data quality in both research and operational settings. Recently, the ARRC has developed several techniques to enhance range and angular resolution using oversampling. The redundant information from overlapped radar resolution volumes are used to adaptively deconvolve oversampled signals to resolve structures and dynamics at a scale smaller than typical resolution. Some of the techniques are applicable to future phased array radar systems, which could provide a cost-effective solution for multi-mission needs.

In addition to higher resolution, range oversampled signals can be transformed via decorrelation to increase the number of independent samples in order to estimate their corresponding Doppler spectrum, its moments, as well as several polarimetric variables on pulsed radars. This technique can be exploited in a combination of faster data temporal acquisition and denser spatial sampling as needed to satisfy some of the evolutionary requirements for the NEXRAD network as well as future multi-mission radar systems. Preliminary results have demonstrated that techniques employing range oversampling are capable of maintaining data quality without sacrificing acquisition time, which lend themselves to future enhancements of the national network of weather surveillance radars. ARRC members are also engaged in research related to clutter mitigation for weather radars and wind profilers through the development and implementation of novel filtering techniques in the time, frequency, and spatial domains. Furthermore, in most weather radars the range and Doppler velocity ambiguity problems are coupled such that trying to alleviate one simply worsens the other. To address this long-standing problem, the two techniques of system phased coding and staggered pulse repetition time have emerged as viable candidates for the NEXRAD network. The two techniques are complementary since they offer advantages at specific elevation angles; hence, they can be simultaneously incorporated into the same volume coverage pattern (or scanning strategy). Both techniques reduce the amount of purple haze obscuration currently encountered during the observation of severe phenomena, as shown in Figure 6.

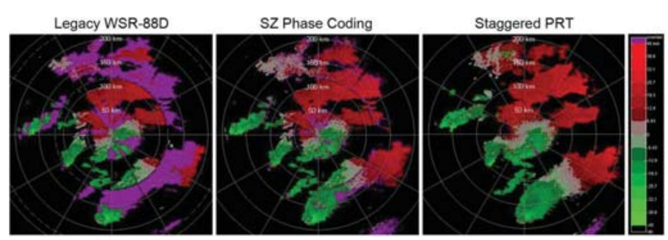

Figure 6. Doppler velocity PPI displays of severe storms in central Oklahoma obtained using legacy signal processing (left panel), systematic phase coding (center panel), and staggered PRT (right panel) algorithms. Purple color denotes an unrecoverable Doppler velocity due to overlaid echoes. Both systematic phase coding and staggered PRT techniques remove significant amounts of purple haze, resulting in displays with larger areas of recovered Doppler velocities.

The ARRC has also worked closely with the local weather forecasting office to develop automated radar algorithms to improve warning of severe storms. A hybrid tornado detection algorithm based on fuzzy logic and neural networks has been developed and tested within the ARRC, and was sponsored through NOAA's CSTAR program. It has been shown that the neuro-fuzzy detection algorithm (NFTDA) can provide improved detection with lower false alarm rates and extended detection range. Preliminary results are shown in Figure 7 for the May 9, 2003 tornado near Oklahoma City.

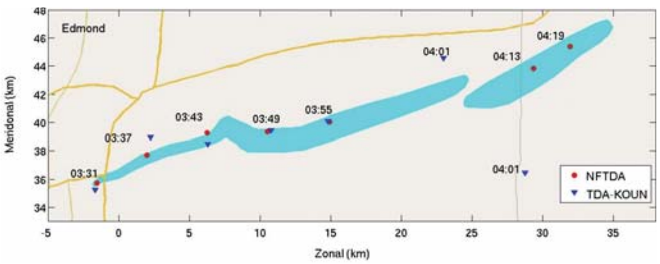

Figure 7. Comparison of tornado detection results from NFTDA (red circles) and operational detection algorithm (TDA, blue triangles). The x-axis is the east-west distance from the radar and the y-axis denotes the north-south distance. Tornado damage paths of May 9, 2003 tornadoes in Central Oklahoma are denoted by the blue shaded regions. It is evident that NFTDA produces more accurate and robust results, especially at 0413 and 0419 UTC, while the conventional Tornado Detection Algorithm (TDA-KOUN) did not report any tornado.

4.4 Observational Studies of the Atmosphere

Atmospheric research within the ARRC embodies a diverse spectrum of topics covering a wide range of spatial and temporal scales. Areas of investigation extend from the Earth's surface upwards to heights of 100 km. Consequently, the members of the ARRC incorporate observations from a variety of radar platforms and radar techniques into their investigations. For example, we are using long wavelength radars located above the Arctic Circle to study the evolution of plasma trails left by meteors as they enter the Earth's atmosphere and ablate (at heights between 80 and 100 km). From these observations, it is possible to estimate the temperature, chemical composition, and wind field representative of the heights at which the meteors disintegrate. Additionally, upper atmosphere radars are used to study ice clouds that form at high latitudes around 85 km above the Earth. Although very little water vapor is present at these heights, the temperatures can be as low as 100 K, which is well below the frost point for the formation of ice particles. There has been a noticeable increase in the occurrence of the upper altitude clouds, which some scientists attribute to an increase in greenhouse gases.

In contrast to these measurements, the ARRC boundary layer radar (BLR) is being used to investigate the dynamic and thermodynamic properties of the daytime convective boundary. The boundary layer is that layer of the atmosphere, which is most strongly coupled with the planetary surface. Measurements from the 33-cm radar are being combined with high spatial and temporal resolution large eddy simulation data, which together provide valuable information on the evolution of the boundary layer depth, its turbulence properties, and how it interacts with the free troposphere above. The BLR is additionally being used in a detailed study of precipitation microphysics. For example, this vertically pointing radar can observe the transition of precipitation from snow into rain as it falls through the height of the freezing level.

Observations from the BLR are being studied in conjunction with measurements from weather radars and in-situ instrumentation. These radars include the mobile SMART radars (see Figure 8), which are currently being upgraded to provide polarization diversity that can improve quantitative rainfall estimation and yield insight into the microphysical structure of clouds, and the mobile NSSL-OU X-band dual-polarimetric (NO-XP) radar. Since lightning depends on the charge separated through the collisions of ice and supercooled water particles above the freezing level, polarization diversity radars are important tools in cloud electrification studies. The mobile C-band Doppler radars have also been used to study severe thunderstorms, including tornadoes, and the evolution of the fine-scale structure of land-falling hurricanes. Hence, research conducted within the ARRC spans micro-scale to hurricane-scale phenomena from the Earth's boundary layer through the mesosphere.

Figure 8: Photograph of one of the two SMART radars during a downdraft haboob event in Arizona. One of the SMART radars will soon be upgraded with dual-polarization capability allowing many new research areas.

4.5 Atmospheric Quantification/Validation and Forecast

Accurate radar measurements allow improved quantification and forecasting of the atmosphere in both clear-air and active weather conditions. Scientists within the ARRC have developed refined methods of retrieving atmospheric refractivity, which is related to moisture, from the radar signal phase of stationary ground targets. These investigations have led to innovative methods for implementation on shorter wavelength radars. Furthermore, statistical studies have been undertaken on the robustness of these refractivity measurements using extremely short dwell times, allowing the possibility for multi-mission capability on phased array radars.

ARRC members are also studying cloud and precipitation microphysical properties and their parameterization based on video disdrometer, wind profiler, and polarimetric radar observations. The S-band polarimetric KOUN radar is located on OU's north campus and provides measurements of reflectivity, differential reflectivity, co-polar cross-correlation coefficient, and differential phase. The ARRC's two-dimensional video disdrometer (2DVD) is deployed at the OU Kessler Farm Field Laboratory (KFFL), which lies approximately 30 km south of the radar, and measures detailed information about the size, shape, and density of precipitating particles on the ground. Also located at KFFL is a vertically pointing profiling radar (ARRC BLR) and a dense network of rain gauges. The profiling radar is used for investigation of precipitation (or clear-air) characteristics as a function of height. Together, these instruments provide a valuable source of validation and inter-comparison for the dual-polarization measurements of KOUN. ARRC members have developed a related algorithm, which can be used to retrieve hydrometeor drop size distributions (DSD) from polarimetric and profiling radar measurements. Working with the numerical modeling group at OU, ARRC members have used the disdrometer and radar-derived DSDs to improve the parameterization of microphysical processes such as evaporation and accretion. These advanced parameterization schemes have been used to enhance numerical weather forecasting. Furthermore, validation studies of the parameterization schemes are planned using the nascent EML.

Collaborating with NCAR scientists, ARRC members have investigated the impact of microphysics parameterization in the Variational Doppler Radar Analysis System (VDRAS) for convective storm initialization and prediction as shown in Figure 9. Results of 30-min forecasts are compared to those from the Marshall-Palmer (M-P) DSD model used by the original VDRAS and to radar estimates. The top-left panel is the water content estimated from the polarization radar (S-Pol) measurements of Z and ZDR. The top-right panel is reflectivity-based rainwater estimates from the KMLB radar. The water content forecasted using the new model is consistent with the S-Pol radar estimate while the M-P model-based results do not agree with the estimates using either radar. It is found that improved parameterization and accurate initialization improve weather forecasts. As mentioned previously and to better understand cloud and precipitation physics and physical processes, the EML is currently under development within the ARRC.

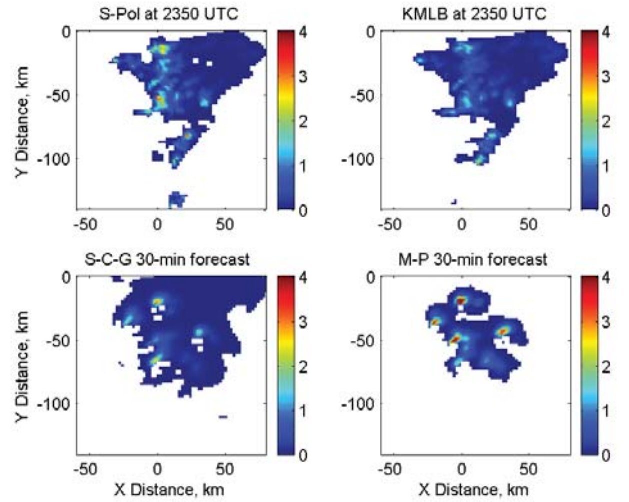

Figure 9. A comparison of low-level rain water content (g m-3) estimated by radars (upper panel) and model forecasts with VDRAS (lower panel) using the new (simplified constrained gamma: S-C-G) and Marshall_Palmer (M_P) DSD models.

5. Summary

The University of Oklahoma has established the Atmospheric Radar Research Center (ARRC), which is an interdisciplinary group of engineers and scientists from the School of Meteorology and the School of Electrical & Computer Engineering. The ARRC is leading OU's educational activities in radar meteorology with the advent of its unique curriculum and emphasis on hands-on participation of the students. Closely coupled with its educational activities, ARRC research is quite broad but follows along the general thrusts of radar system design, phased array radar, signal/array processing, observational studies, and quantitative measurements of the atmosphere. Since its establishment, ARRC members have been able to put forth numerous radar innovations in terms of both algorithms/theory and unique system designs and fabrication.

In our academic setting at the NWC, ARRC members are currently working with numerous groups outside the Norman scientific community and fully welcome new partnerships. In addition, our active research and educational environment allows students (engineering and meteorology) to thrive and grow to their full potential. For more detailed information on the ARRC, see our website at http://arrc.ou.edu or contact us directly for further information.