Final Report, 2016

Title: Retrieval of Boundary Layer 3D Cloud Properties Using Scanning Cloud Radar and 3D Radiative Transfer

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Program: Atmospheric System Research

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Report Sections/Contents:

1. Overview of Project and Results

Retrievals of cloud optical and microphysical properties for boundary layer clouds, including those widely used by ASR investigators, frequently assume that clouds are sufficiently horizontally homogeneous that scattering and absorption (at all wavelengths) can be treated using one dimensional (1D) radiative transfer, and that differences in the field-of-view of different sensors are unimportant. Unfortunately, most boundary layer clouds are far from horizontally homogeneous, and numerous theoretical and observational studies show that the assumption of horizontal homogeneity leads to significant errors. The three dimensional (3D) structure of clouds likewise causes significant difficulties in the evaluation of cloud retrievals. The introduction of scanning cloud and precipitation radars at the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program sites presents opportunities to move beyond the horizontally homogeneous assumption.

The primary objective of this project was to develop a 3D retrieval for warm-phase (liquid only) boundary layer cloud microphysical properties, and to assess errors in current 1D (non-scanning) approaches. The proposed 3D retrieval would be based on observations from the ARM dual-wavelength Ka-band and W-band polarimetric scanning cloud radar, as well as satellite visible and short-wave infrared (SWIR) wavelength imagery (calibrated radiances) in order to provide an additional constraint on the 3D structure. The retrieval was to be developed using a combination of (1) simulated cloud fields (which provides essentially perfect knowledge of the quantities to be retrieved, and permits a detailed quantitative assessment of the retrieval) and (2) ARM radar observations (which naturally are impacted by measurement noise, pointing angle uncertainties and other factors which limit retrievals applied to real observations).

Results for the development based on simulated cloud fields are reported below in Section 2a, and the retrieval results are encouraging. Unfortunately delays and difficulties in getting the ARM scanning radars operational, prevented observations from being gathered that are needed to run and further test the 3D retrieval. Scanning radar patterns where designed and tested, but good quality scanning radar data have not yet been successfully collected by ARM. As a result, the project shifted focus to secondary objectives that included application of radar ARM data to climate model evaluation and testing of microwave radiometer retrievals.

This project provided support for a graduate research student, Wei Zhao, who has used the ARM millimeter cloud radar data record at SGP to study the diurnal cycle of cloud and precipitation. Using a radar simulator and an atmospheric classification scheme (developed under previous ARM funding), Zhao has constructed a climatology of the diurnal cycle at SGP and used this to analyze the diurnal cycle simulated in the Multiscale Modeling Framework (Version 3) climate model. Results are currently being written up for publication, with one paper submitted and another about to be (Zhao et al. 2017a,b). Results of this work are summarized in Section 2b.

This proposal also supported my (PI Marchand's) continued participation in the ARM radar working group and radar simulator development efforts being led by Yuying Zhang and Shaocheng Xie. A Bulletin of the American Meteorological Society (BAMS) article on the ARM radar simulator is about to be submitted (Zhang et al. 2017).

In addition, project funds were used to study precipitation impacts on passive MicroWave Radiometer (MWR) retrievals of cloud Liquid Water Path (LWP). MWRs are the most commonly used and accurate instruments ARM has to retrieve cloud LWP during non-precipitating conditions. Unfortunately current MWR retrievals are often contaminated by precipitation. The present study involved deployment of two MWRs to the University of Washington between Spring and Fall of 2016 to better understand this contamination. A preliminary summary of the project is provided in Section 2c. As part of this activity, we have been working closely with the ARM MWR instrument mentor, Maria Cadeddu, and have been assisting her in the development of MWR retrievals for precipitating conditions. A first paper on this topic has just been submitted to IEEE Transactions on Geosciences (Cadeddu et al. 2017).

2. *Results*

In this section, I provide a brief summary of research results regarding (a) the 3D Retrieval, (b) the Diurnal Cycle Study, and (c) the Microwave Precipitation Study

2A. 3D Retrieval

The ultimate goal of the 3D retrieval is to combine multi-wavelength scanning radar data and multi-wavelength satellite imagery, into a single, self-consistent description of the cloud 3D microphysical structure. Initial development focused on idealized rectangular clouds, and results for this work can be found in our year 1 progress report. During the second year of the project, testing was undertaken using complex clouds extracted from a high-resolution model simulation. In this report we show two examples of this work.

The simulated cloud field was supplied by fellow ASR investigator Graham Feingold, and obtained using his two-moment bin microphysical large-eddy model. Figure 1, below, shows two shallow cumulus cloud (right four panels and left four panels) extracted from the model output. These 3D data were input to a full 3D radiative transfer code to obtain the visible (VIS) and shortwave-infrared (SWIR) radiances that a satellite would observe. The radar reflectivity and satellite reflectances (not shown) are the inputs to the retrieval.

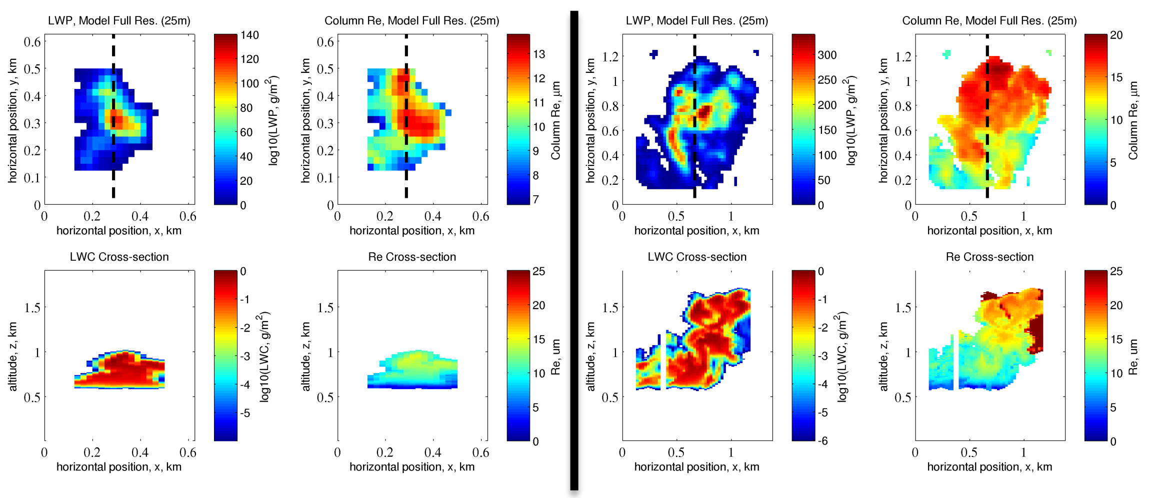

Figure 1 - Examples of two cumulus clouds (left most 4 panels and rightmost 4 panels, respectively) produced by a Large Eddy Simulation (LES) two-moment bin-microphysics model run with a 25m grid spacing. Dashed lines in top panels denote cross-sections shown in lower panels.

Figure 2 shows the retrieval results and the radar data when the simulation is run at a horizontal resolution of 50 to 100m (roughly what we expect the ARM scanning radars will be able to accomplish). Not surprisingly, the radar data (bottom row) play a dominant role in constraining the vertical profile of effective radius (middle row, right panel). The retrieval assumes that the profile of liquid water content is proportional to the square root of the radar reflectivity. This is a reasonable approximation for non-drizzling cumulus and works well in the left case, but limits the retrieval in the drizzling case on the right. Incorporating a second radar wavelength (that is, using the radar dual-wavelength-ratio) is expected to help the simulation in the drizzling case (though the intent of the proposal was to concentrate primarily on non-drizzling clouds).

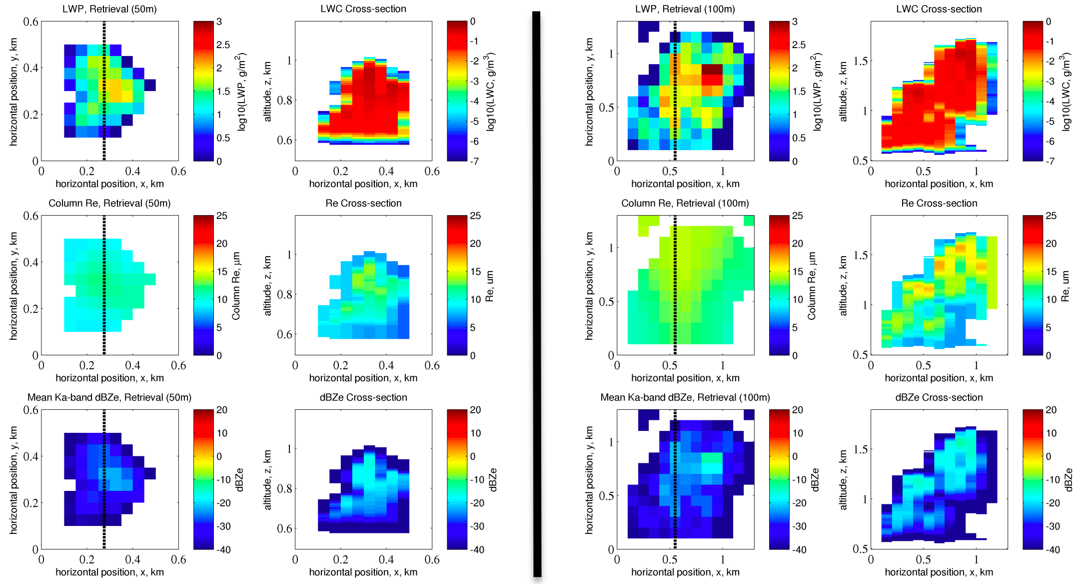

Figure 2 – Top row: retrieved LWP/LWC. Middle row: retrieved effective radius. Bottom row: radar reflectivity.

At this point, my intent is to use actual observations (rather than idealized data from simulated clouds) to continue development of the retrieval, as the retrieval is likely to be impacted significantly by the data quality. It is difficult to gauge the eventual performance of the ARM systems or model realistically the complexity of real radar observations (especially as pertains to dual-wavelength measurements). I remain hopeful that, in spite of many delays and difficulties in getting the ARM scanning radars operational continued development based on ARM observations will be possible in the future and I remain poised to use such data when it becomes available.

<u>2B. Diurnal Cycle Study</u>

The diurnal cycle of clouds and precipitation has strong impacts on the Earth radiative budget via interactions with solar and longwave radiation, and on the hydrological cycle through evaporation and runoff. Given the same temperature and moisture vertical profile, a cloudy night will be warmer at the surface than its cloud-free counterpart because clouds will trap the outgoing longwave radiation in the atmosphere (and less energy is emitted to space); and only clouds that occur during the day can reflect sunlight back into space. Also, precipitation tends to be evaporated faster during daytime than nighttime because daytime often features higher surface temperature and lower relative humidity; and this changes the fraction of runoff versus evaporation, as well as impacting the surface latent and sensible heat fluxes.

Observational studies on the diurnal cycle of precipitation have shown that there is a preferential timing or phase for the maximum occurrence of precipitation that varies from one place to another and from season to season. At SGP there is a nocturnal to early morning precipitation occurrence maximum during the summer season, whereas low clouds are know to occur more often during daytime and high clouds occur more often between late afternoon and the following morning during the warm season. Studies indicate that conventional GCMs generally tend to precipitate too frequently and too early during the day. There have been fewer evaluations of the diurnal cycle of clouds in climate models, but likewise, the studies that do exist show that models struggle to capture the diurnal cycle of both high clouds and low clouds.

ARM datasets offer great potential for evaluating the diurnal cycle of clouds, precipitation and radiation. One attractive approach is to use a radar simulator within a model to facilitate comparisons of ARM radar data with models. Using a radar simulator, one can forward calculate the radar reflectivity profile that the ARM vertically pointing would observe given the models hydrometeors (and other) fields.

Our objectives in this study were, first to identify what diurnal variations are evident in annual and seasonal composites of the ARM MMCR radar reflectivity profile measurements from the SGP. Based on previous work by ASR investigators Zhang and Klein (2010 paper) among others, one expects that (at least) during the summer season, there are significant diurnal variations. Here we group the hydrometeors into three categories, specifically, cloud (reflectivity of -40 to -10 dBZe), drizzle and light precipitation (-10 to +10 dBZe), and heavy precipitation (> +10 dBZe) based upon their reflectivity and examine the frequency of occurrence of each category.

Our second objective is to evaluate the degree to which a cloud radar-simulator in combination with the reflectivity categories might be useful in evaluating climate models, and potentially other models. In particular, we used radar-simulator output from the Multiscale Model Framework (MMF, version 3) climate simulation. The MMF is a GCM (the NCAR CAM model in the present case) with a two-dimensional or small three-dimensional cloud resolving model (CRM) embedded into each GCM grid cell. MMFs have been developed largely to avoid difficulties related to cumulus parameterization in conventional GCMs. The MMF model analyzed in this project has been shown by Marat Khairoutdinov and Mike Pritchard (among others) to better capture the diurnal timing of precipitation in many regions, including some ability to capture the propagation of Mesoscale Convective Systems (MCSs).

A detailed description of the methodology and comparison results is well beyond what can be reported here, but we include below two figures (Figure #3 and #4) from two upcoming papers (one of which has already been submitted) that show the observed and simulated diurnal cycles of hydrometeor occurrence.

To summarize the study results concisely, we find that, in spite of the fact that the ARM radar is vertically pointing (rather than scanning), its data record is long enough to capture important aspects of the diurnal cycle of hydrometeors and provide insight into the diurnal variations of hydrometeor vertical structure. The results of this study also demonstrate that a radar simulator combined with the simple reflectivity-based classification can be an effective approach for evaluating diurnal variations in model hydrometeor occurrence. As regards the MMF itself, the model (*i*) significantly overestimates the occurrence of high cloud and precipitation (and known problem with this model), *(ii)* does not have sufficient low (boundary layer) cloud and does not capture the diurnal cycle of boundary layer clouds, and (*iii*) the overabundance of high cloud and precipitation aside, in the summer the diurnal cycle of high clouds and precipitation in the upper troposphere are reasonably well-represented in the MMF. In particular, the diurnal variation in vertical structure suggests the MMF is capturing MCS propagation during the summer, supporting the conclusions of Mike Pritchard [2011]. In the spring, however, the diurnal cycle is not being captured. We are currently trying to understand why the model does well in summer and poorly in spring.

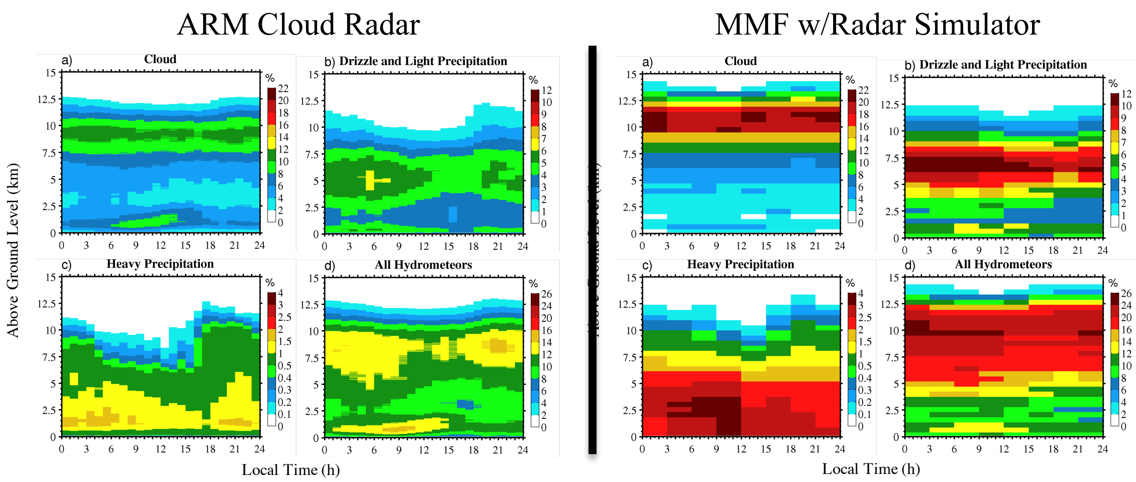

Figure 3. The annual diurnal cycle of hydrometeor occurrence for (a) clouds, (b) drizzle and light precipitation, (c) heavy precipitation and (d) all the hydrometeors (clouds + drizzle and light precipitation + heavy rain) at SGP. Rightmost 4 panels are based on ~14 year MMCR dataset and Leftmost 4 panels are for the MMF model obtained via and instrument simulator.

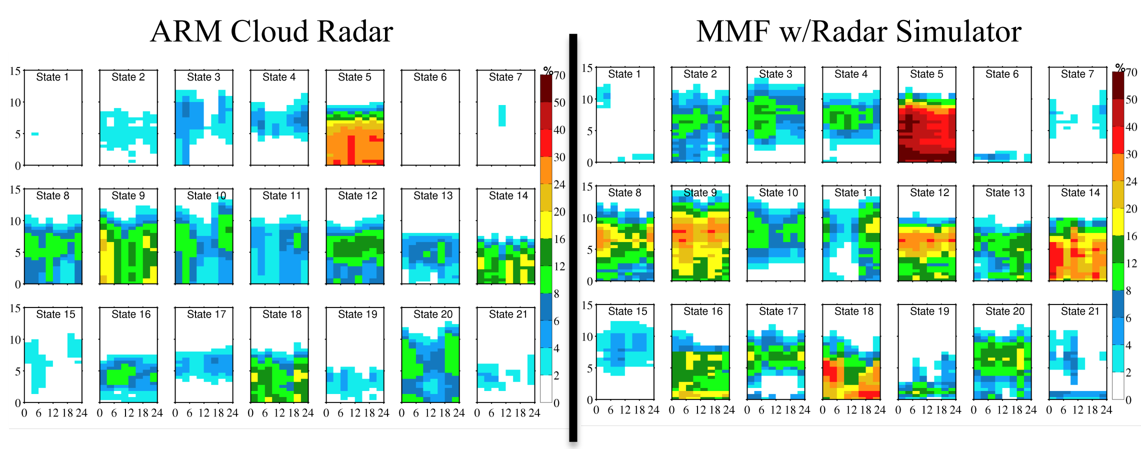

Figure 4. The diurnal cycle of precipitation occurrence (radar reflectivity > -10 dBZe) for 21 atmospheric states (weather patterns). MMF diurnal cycle compares favorability for many states that occur predominately in the summer (e.g. state #9-11) but poorly in some spring states (e.g., state #8 and #20).

2C. Microwave Precipitation Study

Passive MicroWave Radiometers (MWRs) are the most commonly used and accurate instruments ARM has to retrieve cloud Liquid Water Path (LWP), and MWR data (brightness temperatures) are frequently combined with measurements from radar and other instruments for cloud microphysical retrievals. Unfortunately, MWR data are not easily used in precipitating conditions. The reasons for this are two-fold. First, the measurements are "contaminated" by water on the MWR radome, and second, precipitating particles are large enough to scatter (not simply emit) microwave radiation. Traditional MWR retrievals do not include scattering effects, which depend crucially on the particle size. Both wet-radomes and scattering can make a substantial contribution to the measured microwave brightness temperatures and typically result in retrievals of cloud liquid water and column water vapor that are biased high.

While it is sometimes obvious when the wet-radome contamination is large, much of the time it is difficult to know with confidence that the contributions from either a wet-radome or scattering is small. At present there is no attempt to estimate or correct for these effects in ARM cloud LWP retrievals, and identification of poor LWP data is generally left to users. Typically users are advised to simply throw out all data when the MWR "wet window" resistance-based sensor indicates water is present, but this sensor is adjusted by hand and is known to be temperamental.

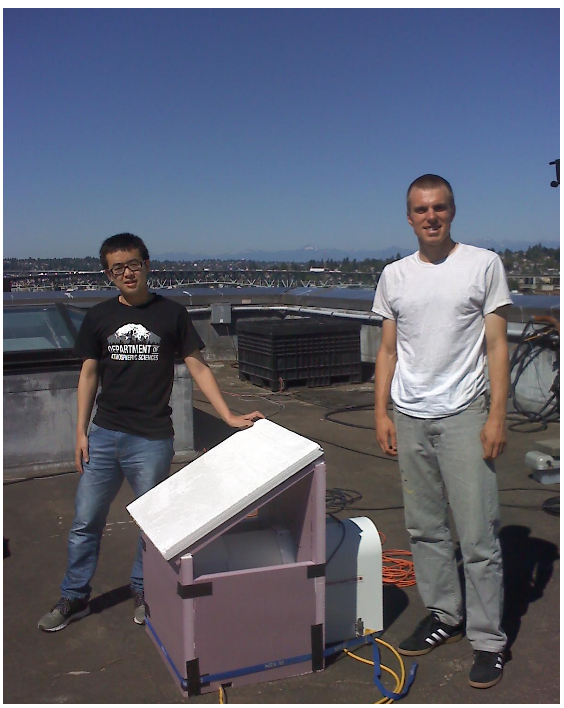

Figure 5 – Graduate students Wei Zhao (left) and Casey Wall (right) standing next to covered radiometer.

To address the current limitations in MWR retrievals during precipitating conditions, a pair of ARM two-channel microwave radiometers was deployed to the University of Washington (UW) in Seattle between spring and fall of 2016. The radiometers were operated in a scanning or tip-cal mode. One radiometer was placed under a cover that prevented this radiometer's radome from gathering water while still permitting MWR measurements away from zenith (Figure #5), while the other radiometer was operated normally (uncovered and with the radome exposed to the sky). We refer to these as the "covered" and "open" radiometers, respectively.

The idea behind this experiment is that while measurements along the off-zenith angles of the covered radiometer will still be affected by scattering, they will not be affected by water on the radome. The open radiometer, on the other hand, will suffer from both scattering and wet radome effects. Comparing the data will thus permit an examination of wet-radome effects in the off-zenith measurements. Further, the covered data might still be used to derive LWP (and water vapor path) by including scattering in the retrieval and might be used to study the angular dependence of the scattering effect.

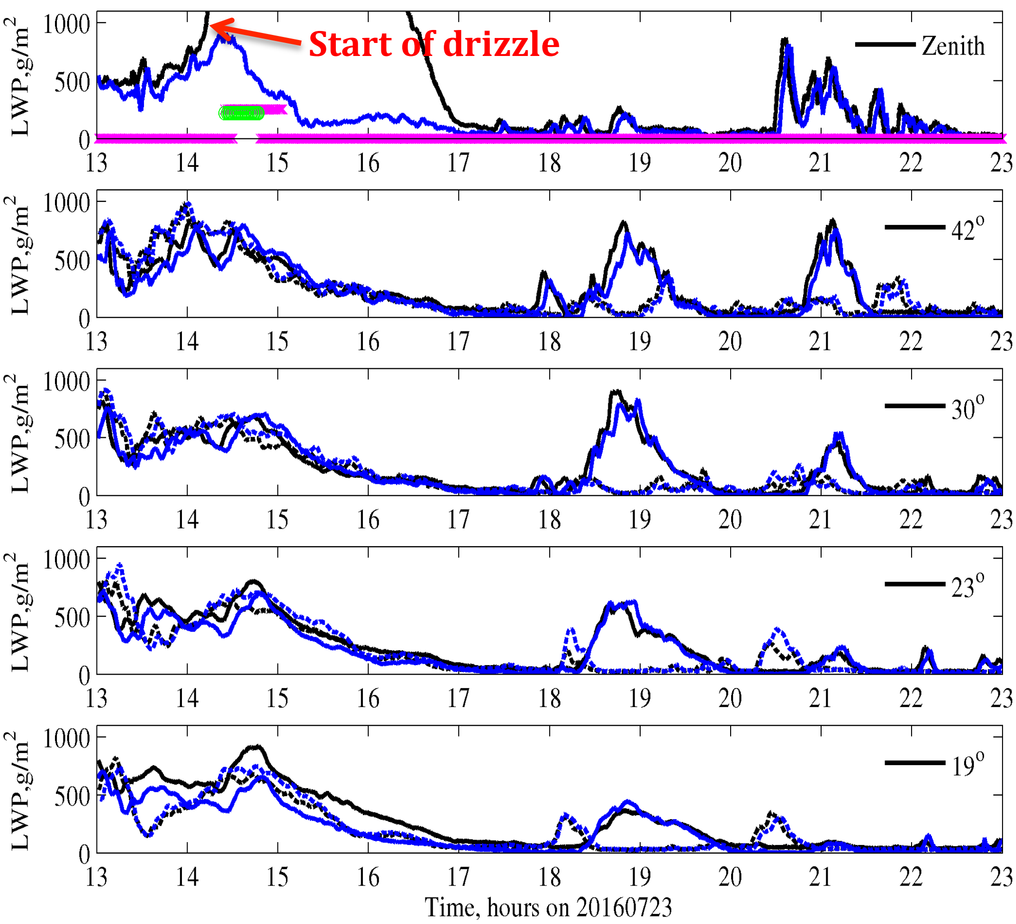

Figure 6. Example of LWP retrieved from MWR data gathering during the Dual MWR Experiment. Away from zenith, solid lines look eastward and solid lines westward. Blue is the open radiometer and black the covered radiometer. The preliminary retrievals are based on physical iterative approach and does NOT account for scattering [Marchand et al .2003].

An example of results from this dual MWR experiment are shown in Figure 6 for one rain/drizzle event. This figure shows the LWP retrieved using a physical-iterative approach that assumes a 1D atmosphere and no scattering [Marchand et al 2003]. Each panel represents measurements and different view angles. The zenith measurement (top panel) from the covered radiometer (black line) top-panel show a marked increase in LWP starting about 14 UTC. There is no blower on top of the cover, and it turns out that this makes the covered radiometer very sensitive to even the lightest of precipitation at zenith. It is clear that drizzle has started before either wet-window sensor notes precipitation is present. The peak values for the LWP retrieval for the open MWR (blue lines) at all off-zenith scan-angles ranges from about 500 to less than 1000 g/m^2. Perhaps surprisingly, the open radiances compare well with values from the covered radiometer off-zenith. This result demonstrates that the blower on the open MWR is working well and there is little if any wet-radome contamination.

An early conclusion of this experiment is that the open radiometer was often free from wet-radome contamination (even when the wet window sensor is wet), suggesting the data can be used for LWP retrievals and studies of scattering effects (which we are doing now with Maria Cadeddu).

3. Papers, Impacts and Ongoing Activities

A list of publication and presentation associated with DOE Award DE-SC0008585 is provided below. There will be additional poster presentations at the 2018 ASR Science team meeting related to the diurnal cycle study and microwave precipitation study. It is also very likely that data gathering during the dual microwave deployment at UW will also be used as part of future papers on MWR retrievals.

From my perspective, it is disappointing that more work on the 3D retrieval was not accomplished during this project. Getting the ARM scanning radars functioning well has proven to be slow, but on the good side I remain well poised to use the ARM scanning radar data in coming years. Also, Wei Zhao and I have used the time well and accomplished considerably more as regards model evaluation and laying the foundation for future studies on the diurnal cycle of clouds and precipitation (via radar simulator), as well as advancing MWR retrievals.

Table #1 – Project supported publications

Primary Publications

Zhao, Wei, Roger Marchand and Qiang Fu, 2017a: The Diurnal Cycle of Clouds and Precipitation at the ARM SGP Site: Cloud Radar Observations and Simulations from the Multiscale Modeling Framework, *submitted Journal of Geophysical Research Atmospheres, December 2016*.

Zhao, Wei, Roger Marchand and Qiang Fu, 2017b: The Diurnal Cycle of Clouds and Precipitation at the ARM SGP Site: Atmospheric State-Based Analysis and Error Decomposition, *in preparation (expect submission in February 2017)*.

Supported Publications

Cadeddu, M. P., R. Marchand, E. Orlandi, D. Turner, M. Mech, 2017: Microwave ground-based retrievals of cloud and rain liquid water path in drizzling and precipitating clouds: Challenges and possibilities., *submitted IEEE Transactions on Geoscience and Remote Sensing,* January 2017.

Zhang Y., S. Xie, S. Klein, R. Marchand, P. Kollias, E. E. Clothiaux, W. Lin, D. Swales, A. Bodas-Salcedo, S. Collis, K. Johnson, M. Jensen, N. Bharadwaj, J. Hardin, B. Isom, 2017: The ARM Cloud Radar Simulator for Global Climate Models A New Tool for Bridging Field Data and Climate Models, *in preparation for submission to Bulletin of the American Meteorological Society (due Jan. 19).*

Related Presentations

Zhao, Wei, Roger Marchand and Qiang Fu, 2016: Diurnal Cycle of Clouds and Precipitation at the ARM SGP Site, *Poster (A43G-0313) at American Geophysical Union (AGU) Fall meeting 2016, San Francisco, CA.*

Zhao, Wei, Roger Marchand and Qiang Fu, 2016: Diurnal Cycle of Clouds and Precipitation at the ARM SGP Site, *Poster ASR Science Team Meeting 2016.*

Marchand, Roger, 2015: Retrieval of Warm Boundary Layer Cloud Properties in Three Dimensions, *Poster ASR Science Team Meeting 2015.*