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ARM Cloud and Precipitation Measurements and Science Group (CPMSG) 2024 Workshop Report

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Acronyms and Abbreviations

3D	three-dimensional
3D-VAR	Three-dimensional Constrained Variational Analysis Value-Added Product
ACE-ENA	Aerosol and Cloud Experiments in the Eastern North Atlantic
AI	artificial intelligence
AMF	ARM Mobile Facility
AMIE-GAN	ARM Madden-Julian Oscillation Investigation Experiment – Gan Island
ARM	Atmospheric Radiation Measurement
ARSCL	Active Remote Sensing of Clouds Value-Added Product
ASR	Atmospheric System Research
AWARE	ARM West Antarctic Radiation Experiment
CCN	cloud condensation nuclei
CPMSG	Cloud and Precipitation Measurements and Science Group
DOE	U.S. Department of Energy
DP-SCREAM	doubly periodic SCREAM
ENA	Eastern North Atlantic
ESM	Earth system model
FAA	Federal Aviation Administration
FTE	Full-Time Effort
GARP	Global Atmospheric Research Programme
GATE	GARP Atlantic Tropical Experiment
GE	general mode
HID	hydrometeor identification
HSRL	high-spectral-resolution lidar
IOP	intensive operational period
KAZR	Ka ARM Zenith Radar
LASSO	LES ARM Symbiotic Simulation and Observation
LDR	linear depolarization ratio
LES	large-eddy simulation
MASC	Multi-Angle Snowflake Camera
MC3E	Midlatitude Continental Convective Clouds Experiment
MD	moderate sensitivity mode
MICROBASE	Continuous Baseline Microphysical Retrieval Value-Added Product
MOSAiC	Multidisciplinary Drifting Observatory for the Study of Arctic Climate
NDROP	Droplet Number Concentration Value-Added Product
NSA	North Slope of Alaska

OSSE	Observation System Simulation Experiment
PI	principal investigator
PIP	Precipitation Imaging Package
RaDCLss	Radar Columns and In Situ Sensors Value-Added Product
SAIL	Surface Atmosphere Integrated Field Laboratory
SCREAM	Simple Cloud-Resolving E3SM Atmosphere Model
SGP	Southern Great Plains
SIP	secondary ice production
SQUIRE	Surface Quantitative Precipitation Estimation Value-Added Product
SST	sea surface temperature
THREAD	Tying in High Resolution E3SM with ARM Data
TRL	Technical Readiness Level
UAS	uncrewed aerial system(s)
VAP	value-added product

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1.0 Introduction

The mission of the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility is to improve the understanding and representation of cloud and aerosol processes and their interaction with the Earth's surface in Earth system models (ESMs) by providing comprehensive field observations and supporting advanced data analytics. The ARM Cloud and Precipitation Measurements and Science Group (CPMSG) was chartered in March 2019 to help improve the performance and scientific impact of ARM measurements of clouds and precipitation. The group aims to identify and address gaps in measurement capabilities, maximize the scientific impact of ARM data, and effectively serve the scientific community. To achieve these goals, the group includes experts in cloud and precipitation science, as well as representatives from ARM infrastructure, including instrument mentors, engineers, data quality officers, and data product translators.

Prior to CPMSG, early discussions on cloud and precipitation measurements primarily focused on improving radar systems, but have since evolved to include a broader scope involving radiometers and other instruments. Since its formation, the CPMSG has gathered feedback using science traceability matrices. CPMSG aims to keep these as living documents to show the measurement needs, scientific drivers, roadblocks, maturity of measurements and retrievals, and pathways to model improvements. The group meets quarterly to discuss and prioritize measurement and operational improvements.

1.1 Grand Challenges in Earth System Models[1]

ARM Cloud and precipitation measurements have been extensively used to assess regime-dependent precipitation characteristics, the transition from shallow to deep convection, and diurnal cycles in ESMs. These comparisons are essential for improving ESMs, as global atmospheric models can approximately capture the mean state and long-term trends but often struggle with accurately representing precipitation phase, amplitude, and distributions at both global and regional scales. Three emerging challenges are identified in the context of ESMs:

- Sea surface temperature (SST) pattern issues: ESMs struggle to represent SST pattern changes accurately, impacting predictions of precipitation distributions and extreme events.
- Out-of-sample issues: Models tuned for pre-industrial and modern climates may fail in other conditions, as shown in paleoclimate simulations.
- Fit-for-purpose problems: Current models lack the realistic physical representation to accurately capture cloud and precipitation processes (such as aerosol-cloud interactions and cloud feedback), limiting their reliability in estimating their response to different climate scenarios. In other words, the models can be unfit for the purposes for which they are applied.

The importance of vertical velocity measurements has been repeatedly stressed for improved model representation of cloud and precipitation processes, especially those related to convection and aerosol interactions. Machine learning techniques have also shown great promise in emulating processes in

[1] Based on the plenary presentation by Dr. Leo Donner.

high-resolution models, which could potentially overcome the limitations of traditional approaches in parameterizations of cloud and precipitation processes. From the perspective of ARM, machine learning is a great tool to bridge small-scale, detailed observations and large-scale model simulations.

The integration between laboratory-based research, field measurements, and high-resolution modeling is critical as emerging climate challenges demand more detailed process understanding. To ensure significant progress in ESMs, collaboration across the laboratory, observational, and modeling communities was repeatedly emphasized.

2.0 Workshop Goals

This workshop aims to generate actionable recommendations for ARM, focusing on addressing measurement gaps and advancing cloud and precipitation science. Guided by the measurement priorities outlined in the ARM Decadal Vision, the workshop centered on four key discussion topics. These topics were chosen to reflect both pressing challenges and areas of significant progress, ensuring that the limited workshop time yields the greatest possible impact. These topics include:

- Cloud droplet number concentration and warm rain from surface to sub-cloud layer
- Surface solid precipitation
- Ice-containing clouds
- Vertical air motion below cloud base and in clouds.

Beyond the four main topic areas, a plenary session was devoted to developing science-based strategies that account for the rapid advancement of machine learning and to fostering stronger collaborations between observational and modeling communities, as well as across modeling scales. While the workshop primarily focused on predefined topics, participants were encouraged to consider broader grand challenges in Earth system models and to share ideas beyond the set topics. Insights from the workshop will contribute to a paper outlining key recommendations for a broader scientific impact.

3.0 Topical Discussions and Actions

Two invited speakers opened each topical session to provide an overview of the science requirement of observables and modeling needs, followed by a review of measurement techniques, discussions initiated with the framing questions, and recommendations.

3.1 Warm Clouds and Precipitation[2]

This session focused on the microphysical properties of warm clouds for studying precipitation processes and aerosol-cloud interactions. Invited speakers highlighted the critical importance of measuring changes in cloud droplet number concentration. They also stressed the need for collocated measurements of

[2] Authors: Christine Chiu and Damao Zhang. Presenters: Haonan Chen, Christine Chiu, Po-Lun Ma, Rob Newsom, Christopher Williams, Tianle Yuan, and Zeen Zhu.

aerosols, clouds, precipitation, and meteorological conditions to enhance model evaluation and enable process-oriented diagnostics and constraints. The objective is not only to accurately capture the state of key variables but also to understand the underlying drivers and processes leading to that state. To improve process representation, discussions emphasized advancing process-level understanding, as well as exploring and applying data-driven approaches. Finally, efforts should extend beyond process-level insights to bridge the gap between processes scales and weather and climate scales. Strong collaboration between observationalists and modelers was identified as essential for success.

3.1.1 Cloud Droplet Number Concentration

Cloud droplet number concentration (N_c) is one of the key observables for characterizing rain formation processes and quantifying aerosol-cloud interactions. Several retrieval methods for N_c exist, which can be categorized based on their use of measurements: passive-only (e.g., combined flux and microwave radiometer measurements as used in one of ARM value added products (VAPs) called Droplet Number Concentration (NDROP; Riihimaki et al. 2021)), lidar-only, and synergistic passive and active methods (e.g., microwave radiometer and radar, or shortwave radiation combined with radar). These methods have been published in peer-reviewed journals and are all relatively mature. However, discrepancies among existing N_c retrievals need to be reduced to better constrain cloud process rates and aerosol-cloud interactions. Given the scientific importance of this observable, the source of the retrieval discrepancies needs to be identified, and retrievals should reach some consensus so that ARM can develop a unified product with proper uncertainty estimates. Participants emphasized the need for comprehensive intercomparison studies using synthetic observations or golden cases.

Many published retrieval methods that incorporate radar measurements have relied on ARM Active Remote Sensing of Clouds (ARSCL) data products, which contain uncalibrated measurements from the general mode (GE) and moderate sensitivity mode (MD). In ARSCL, radar gates below 3 km use GE measurements, while those above 3 km use MD measurements. Many cases are found to suffer from the range sidelobe problem – unphysical weak radar echoes that exceed the noise floor at cloud tops – leading to erroneous cloud-top heights and temporal variations. While N_c retrievals are not sensitive to the location and reflectivity of cloud tops, the existing retrievals can still be used for understanding cloud properties. However, this sidelobe issue can significantly impact cloud-top entrainment estimates. Since studies using N_c often seek to understand the role of entrainment, this sidelobe issue should be addressed. Applying screening techniques – whether through existing methods (e.g., Westbrook and Nicole 2013) or by revisiting the thresholds in the current radar plan (Feng et al. 2024) – and establishing a workflow to integrate cleaned radar reflectivity back into ARSCL and other radar products will greatly enhance the scientific value of ARM radar observations.

To enhance ARM cloud droplet number concentration products, **the following recommendations are made:**

1. **Organize an intercomparison activity** to identify the sources of retrieval discrepancies and develop a unified product with appropriate uncertainty estimates. This effort should involve careful calibration of measurements, systematic comparisons of retrieval assumptions, and transparent access to methodological details for users. Each retrieval method should provide properly characterized uncertainty estimates, including uncertainty in measurement and input parameters used in the retrievals. A logical starting point would be synthetic measurements and case studies from the Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) field campaigns, where in

situ aircraft data are available as a reference. Outcomes from this activity will help ARM consolidate parallel retrieval efforts into a single, user-friendly data product.

2. **Expand collocated in situ aircraft and ground-based cloud and precipitation observations.** Currently, such data sets remain limited, posing challenges for evaluating retrieval accuracy. Even within ACE-ENA, only a few flights were sufficiently close to the ARM fixed site for robust intercomparison, limiting statistical confidence. Addressing this gap is crucial, as ARM is the unique provider of a long-term data set of cloud droplet number concentration with high temporal resolution in the marine environment.
3. **Reassess data products periodically**, e.g., every five years, to incorporate methodological advancements and user feedback.
4. **Address the cloud-top sidelobe issue**, e.g., by refining existing screening techniques and implementing a workflow that ensures consistency across ARM's cloud radar data sets and products.

3.1.2 Precipitation in Sub-Cloud Layers

The method developed by O'Connor et al. (2005) is widely used by the community to retrieve drizzle properties in sub-cloud layers by combining Doppler radar and ceilometer (or lidar) measurements. Many research groups have implemented their own versions of this method, yet their retrievals can differ due to variations in lidar and radar calibration procedures applied by users (e.g., Kotthaus et al. 2016) and differences in approximating Doppler spectral width contributions from turbulence and radar finite field of view. Given that this retrieval method is well established, implementing it as a VAP would address the needs of ARM users who may lack the expertise to process lidar and radar data independently.

While Doppler radar spectra are commonly used for drizzle retrievals, Doppler lidar spectra also contain valuable drizzle information that has not yet been fully explored or routinely archived in the ARM data repository. However, the substantial data volume presents a challenge. A potential solution is to implement real-time drizzle detection using Doppler lidar spectra and store the spectral data only when drizzle is present. This approach would provide ARM users with additional information to improve drizzle retrievals while minimizing data storage concerns. Given the rich information contained in Doppler spectra and the feasibility of this targeted storage solution, this addition is recommended.

To enhance ARM sub-cloud drizzle products, **the following recommendations are made**:

5. Implement ceilometer calibration procedures (O'Connor et al. 2004) and sub-cloud drizzle retrieval (O'Connor et al. 2005) for stratocumulus regime. ARM can work with principal investigators who are willing to share the code to calibrate ceilometer measurements and retrieve drizzle water content and effective radius in the sub-cloud layers. Additionally, drizzle evaporation rates can be computed accordingly and would be invaluable for the ARM community to understand the drizzle impact on cloud and boundary-layer dynamics.
6. **Store lidar Doppler spectrum** when drizzle is detected.

3.1.3 Liquid Precipitation at the Surface

ARM operates two types of rain gauges and three types of disdrometers, providing over 20 years of surface liquid precipitation measurements. The required temporal resolution of surface precipitation data varies depending on the scientific application. Some model evaluations rely on lower-resolution data, while others require higher-resolution measurements to track precipitation features in detail.

The cumulative precipitation discrepancy between different disdrometers and rain gauges over 18 months at the Southern Great Plains (SGP) site ranges from 6% to 18% (Wang et al. 2021). This variation is expected due to differences in instrument sampling areas, the natural spatial and intensity variability of rainfall systems, and the influence of high winds. Given the importance of accurate surface precipitation measurements, understanding and characterizing these discrepancies remains a priority.

To complement direct surface measurements, a machine-learning-based method has been introduced to estimate surface precipitation using radar scans (Li et al. 2023; 2024a, b). By incorporating multiple radar observables at various elevation angles, this approach captures detailed raindrop properties and their vertical structures. This technique shows promise in bridging the connection between atmospheric cloud processes and ground-level precipitation, potentially improving measurement consistency.

To enhance the scientific impact of ARM liquid precipitation measurements at the surface, **the following recommendations are made**:

7. **Develop benchmark data sets with well-characterized uncertainties.** This effort involves collaboration with instrument vendors to understand built-in algorithmic processing and establish calibration standards across different instruments. Additionally, dedicated intercomparison campaigns may be necessary to ensure precipitation measurement consistency. Close coordination between ARM instrument mentors and data analysts is essential and recommended to provide a unified precipitation data set with appropriate uncertainty quantification.
8. **Make the benchmark data sets artificial intelligence (AI)-ready.** Such long-term benchmark data sets are critical assets for evaluating remote-sensing retrievals and model simulations across various precipitation regimes. Given the strong interest in estimating liquid precipitation using remote-sensing measurements – including ground-based radars and satellite observations – through machine-learning techniques, these data sets can serve as ground truth for training. To maximize their utility for AI applications, careful attention must be given to data format, cleanliness, and uncertainty estimates.

3.1.4 Additional Recommendations

For model evaluations, simulators for both instruments and data products (e.g., ARSCL) would be highly valuable. Establishing a clear workflow for retrievals and VAPs is essential to help users differentiate between various retrieval methods. Additionally, ensuring high-quality data and retrievals for intensive operational period (IOP) cases, as well as cases used in the Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO; Gustafson et al. 2020a, 2020b, 2023), would provide critical support for observational and modeling studies.

3.2 Solid Precipitation at the Surface[3]

ARM's deployments in regimes for solid precipitation, particularly at challenging locations like the North Slope of Alaska (NSA) and field campaigns such as the Surface Atmosphere Integrated Field Laboratory (SAIL), demonstrate a comprehensive and multifaceted approach to understanding snowfall processes and their interactions with the energy and water cycles. These deployments leverage a diverse array of instruments to capture various aspects of solid precipitation, each with its own strengths and limitations. ARM has been actively advancing its solid precipitation measurements at the NSA observatory with the addition of solid-precipitation-focused instrumentation at the main site and the implementation of an extended facility further inland to better characterize the inland precipitation gradients.

This breakout session covered scientific insights into solid precipitation using ARM measurements, existing capabilities in both the in situ (see Table 1) and remote observations, existing and potential retrievals, and machine-learning possibilities to improve retrievals.

Table 1. Location of various in situ precipitation instrumentation deployed by ARM. Blue shading indicates ARM instrumentation specific for solid-precipitation.

	SGP	NSA	ENA	AMF1	AMF2	AMF3	Comments
Tipping Bucket Rain Gauge (STAMP)	X					X	
Tipping Bucket Rain Gauge (MET)	X		X	X	X	X	
Pluvio2 Weighing Bucket	X		X	X	X	X	
Optical Rain Gauge (MET)	X		X	X	X	X	Main site
Present Weather Detector (MET)	X	X	X	X	X	X	Main site
Impact Rain Gauge (AOSMET)	X		X	X	X	X	
Impact Disdrometer	X						
Parsivel Disdrometer	X		X	X	X	X	
2D Video Disdrometer	X		X	X	X	X	
Geonor Weighing Bucket		X					
Laser Precipitation Monitor		X					
Sonic Ranging Sensor		X					
Multi-Angle Snowflake Camera		X					
Solid Particle Mass Flux		X					
Precipitation Imaging Package		X					

The following recommendations emerged from the breakout session:

Recommendation 1: Improve quality of ARM in situ measurements and data products.

ARM deploys a variety of instruments that exhibit advantages and disadvantages depending on the precipitation type and rates being observed. It is important that ARM continues to advance its understanding of these instruments, improving the data products and quality control for ARM users. It is important to compare against non-ARM gauges where possible. In particular, it would be valuable to

[3] Authors: Adam Theisen and Joseph O'Brien. Presenters: Fraser King, Sergey Matrosov, Joseph O'Brien, Matthew Sturm, and Adam Theisen.

understand how laser (e.g., laser disdrometer [LDIS]) and optical systems (e.g., optical rain gauge [ORG] and present weather detector [PWD]) report snowfall.

For solid precipitation at NSA, it is important that these products be advanced to quality-controlled b-level data products with quantities valuable to the user community. It would be beneficial for ARM to leverage existing open-source codes to further advance and refine existing data products, such as that from the Precipitation Imaging Package (PIP).

Additionally, ARM should prioritize efforts to quantify and document retrieval uncertainties across its snow-based measurement systems, ensuring that users have a clearer understanding of data confidence levels. Well-characterized uncertainty bounds provide significant value to users, including climate model developers.

Recommendation 2: Advance ARM Value-Added Products for Solid Precipitation

Snow retrievals from Ka ARM Zenith Radar (KAZR) measurements are less affected by blowing snow and offer high-temporal-resolution data, but their radar-snow relationships still require careful validation. It would be beneficial for ARM to implement a VAP related to snowfall retrievals from the KAZR similar to past principal investigator (PI) products. Additionally, further implementing VAPs relevant to snowfall at NSA such as Surface Quantitative Precipitation Estimation (SQUIRE) and Radar Columns and In Situ Sensors (RaDCLss) will be important for furthering science at NSA. The application of machine-learning techniques, such as those deployed by DeepPrecip (King et al. 2022), could provide more robust and accurate retrievals of precipitation.

Recommendation 3: Instrumentation Advancement

Wind shielding is extremely important for in situ measurements to reduce the impact of blowing snow and the accumulation of snow in the measurement area. Existing ARM wind shields are failing and there is a need to develop new, more robust solutions. While seemingly small, the ability to develop a suitable replacement will have a large impact on the quality of the data.

Polarimetric lidars can provide retrievals of blowing snow in the lowest portions of the atmosphere. Ceilometers, especially, can observe the atmosphere closer to the ground than other lidar systems. It would be beneficial to deploy a polarimetric ceilometer at NSA to inform the in situ observations further.

Recommendation 4: Measurement Integration

While it is important to advance individual areas, such as instrumentation, data products, retrievals, etc., a more transformative approach would be to provide integrated products to the users geared toward better understanding solid precipitation measurements. This includes both the use of in situ and remote sensing to develop both that broader scale understanding and the local understanding of solid precipitation.

In summary, ARM's deployments in solid precipitation regimes, particularly in challenging environments like NSA, showcase a robust and adaptive approach to precipitation measurement. By employing a diverse set of instruments, addressing measurement challenges, and focusing on data integration and retrieval improvements, ARM is well positioned to advance our understanding of snowfall processes and their impacts on the energy and water cycles. Continued efforts to enhance sensor calibration, develop higher-level data products, and improve wind shielding for instruments will further strengthen ARM's capabilities in capturing accurate and reliable precipitation data, ultimately contributing to more effective climate modeling and water resource management.

3.3 Ice-Containing Clouds[4]

The ice-containing cloud measurement and science breakout session focused on ice-related scientific needs and how ARM can address them. The session began with an overview of scientific needs from the observational perspective, followed by an equivalent presentation about needs from the modeling perspective. An overview of remote-sensing retrievals of ice properties, the status of ARM radars, and potential plans to meet scientific needs were also presented to facilitate group discussions.

The breakout discussion covered multiple topics related to ARM operations and activities, including measurement acquisition, retrieval development, retrieval automation, and ARM deployments. Below is an overview of the topics discussed, followed by recommendations for ARM.

- Attendees discussed the need for comprehensive measurements taken in tandem (preferentially, Lagrangian, and at a high resolution) given the limited ability to observe and track some, if any, ice processes in nature.
- Drones (and other uncrewed aerial systems [UAS]) as means of acquiring, in certain conditions, in situ observations within mixed-phase clouds.
- Observational limitations: for example, in situ aircraft measurement constraints (e.g., we are still challenged by detecting small ice < 100 µm) and surface measurements such as disdrometers and imagers not reflecting ice particle properties (e.g., fall speed) in or close to their generating regions aloft.
- Deployment to observationally deficient regions and regimes such as remote sites and deep convection (ideas were raised about potentially deploying an ARM Mobile Facility (AMF) on an aircraft carrier, oil drilling platform, or remote island).
- Related to the previous item, comprehensive multi-agency deployments at scales of the Midlatitude Continental Convective Clouds Experiment (MC3E) or even the Global Atmospheric Research Programme (GARP) Atlantic Tropical Experiment (GATE), were discussed. These included the need for co-location of in situ deep convection samples with dual Doppler measurements to establish spatial mapping of updrafts versus ice properties, and questions such as how can we theoretically coordinate across agencies to get such a “dream campaign”?
- Acquiring secondary ice production (SIP) information: limited ability to discern processes using remote sensing and in situ; laboratory studies are most informative about these processes. Mountain-top deployments were discussed as potential locations for deployments with a SIP focus that could also ameliorate surface ice observation limitations (as mentioned above) to some extent.
- Lagrangian considerations and potential deployments: for example, using aircraft or UAS to examine air transformation and marine cloud brightening or disentangling biological ice-nucleating particles and SIP; upstream measurements of airmasses predicted to be entrained into convective systems over

[4] Author: Israel Silber. Presenters: Ya-Chien Feng, Greg McFarquhar, Israel Silber, Xue Zheng.

AMFs. Such campaigns can be performed even considering Federal Aviation Administration (FAA) limitations on UAS in-cloud flights.

- Decomposition of radar spectra will help facilitate better retrievals and characterization of conditions. For example, the detection of SIP via high linear depolarization ratio (LDR) of a Doppler radar spectrum population.
- Ice retrieval fidelity and uncertainties: discussion focused on perturbing the retrieval input parameter space and using multiple retrievals to evaluate structural differences between retrieval algorithms. The deficiency of ice models describing extremely small or large aspect ratios (dendritic or columnar habit ice particles) was mentioned.
- Consistency between numerical models and retrievals: transparency and sharing of basic information about implemented assumptions and different representations in retrievals and models (such as fall speed and ice shape parameterizations) are required.

Recommendations:

Ice retrievals and retrieval development:

1. The current ARM VAPs providing ice properties (i.e., Continuous Baseline Microphysical Retrieval [MICROBASE]) use fully empirical formulas that are not generalized in any form. More advanced and comprehensive retrieval frameworks exist and could be adapted by ARM.
2. Because of the high number of free variables in ice retrievals, ARM retrievals of such properties should provide uncertainties that incorporate exploring the sensitivity of retrieval output to input parameter perturbations (e.g., using Bayesian inference techniques).
3. ARM should strive to provide multiple ice retrievals (e.g., retrieval bundles), preferentially based on different instrument combinations. Modelers and others using such bundles are better positioned to evaluate retrieval robustness and therefore more likely to incorporate them in their analyses. Follow-up surveys for users would offer insights into research needs.
4. Ice retrieval developers should work with modelers (discuss and coordinate retrieval-model assumptions, testing the plausibility and impact of assumptions on retrieved quantities, etc.). Organizing an ice-retrieval and modeling intercomparison event or a small group hackathon could drive significant progress in this field.

ARM data processing:

5. ARM is encouraged to leverage vertically pointing radars to their maximum by implementing the decomposition of radar spectra as automated b- or c-level data sets. This spectral decomposition will open new avenues for more robust retrievals (among others, of ice properties, rain, and secondary ice production detection), and will augment process understanding using ARM data (e.g., by analyzing multiple hydrometeor populations observed in the same radar volume).
6. With the need for small ice measurements, ARM could revisit the basic-level processing of 00 to a1 spectra files. The decision of which radar range gate spectra should be retained is currently made using a noise-filtering approach from legacy radar systems, which is prone to overlooking weaker echoes (e.g., from cirrus or smaller ice and drops). This processing could be revised using newer methods.

ARM deployments:

7. The scientific community would benefit from cross-cutting, likely multi-agency, deployments that will include ground-based and in situ airborne measurements. A potential focus of such deployments is deep convection and anvil cloud life cycles or remote oceanic environments.
8. More deployments in elevated sites (e.g., mountain tops). ARM collected data from SAIL, but it appears that a greater database of surface ice measurements (Precipitation Imaging Package [PIP], Multi-Angle Snowflake Camera [MASC], etc.), closer to ice-generating regions, would support stronger constraints on ice representations in retrievals and models.
9. Deployments in remote locations that have not yet been comprehensively explored remain crucial, as demonstrated by previous ARM campaigns such as the ARM Madden-Julian Oscillation Investigation Experiment – Gan Island (AMIE-GAN), the ARM West Antarctic Radiation Experiment (AWARE), and the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC).
10. Deployment of one or more UAS upwind of ARM deployments. Understanding the properties of air entrained into mixed-phase cloud systems would promote closure studies and causal understanding by using observations and model simulations.
11. (More) routine vertically profiling, multi-wavelength, radar (and lidar) measurements (in relation to items 1 to 3 above) — for example, co-located deployment of Raman lidar, high-spectral-resolution lidar (HSRL), and triple wavelength radars for a significant period.

3.4 Vertical Air Motion[5]

With the goal of making actionable recommendations, the Vertical Air Velocity Breakout Session had three objectives. First, quantify the status, maturity, and complexity of remote-sensing vertical air motion retrieval algorithms that use ARM observations. Second, identify which vertical air motion products would advance ASR modeling science. Third, identify gaps that are limiting progress in estimating vertical air motions. This approach can be summarized with three questions: What can be done? Should it be done? And how can we do it better? The approach aimed to remove the decision paralysis that has occurred due to wanting vertical air motion estimates "in all circumstances, and at all times."

Lidars sensitive to the backscattering from aerosols and long-wavelength radars (e.g., radar wind profilers) and sensitive to Bragg scattering from gradients in refractive index are the only two remote-sensing technologies that can directly measure the vertical air motion. In both cases, aerosols and turbulent eddies are assumed to move with the ambient air motion. In all other remote-sensing technologies, the vertical air motion is not directly observed but is retrieved along with, or after, retrieving (or imposing) a hydrometeor size distribution. Thus, most hydrometeor retrieval algorithms either contain a vertical air motion estimate or could be augmented to include an air motion estimate.

The breakout session consisted of one Science Need presentation, four retrieval presentations, and an open discussion. Since aerosol and hydrometeor backscattering characteristics depend on many factors

[5] Authors: Christopher Williams and Virendra Ghate. Presenters: Greg Elsaesser, Virendra Ghate, Paytsar Muradyan, Mariko Oue, Israel Silber, and Christopher Williams.

(e.g., composition, phase, size, and shape), the retrieval presentations centered on the remote-sensing technologies of lidar, cloud radars, radar wind profilers, and scanning radars. For each remote-sensing technology, hydrometeor and vertical air motion retrieval methods were briefly reviewed with the intent of establishing a Technical Readiness Level (TRL) for each method by assessing:

1. Hydrometeor regime (e.g., out of cloud, liquid cloud droplet, frozen particle)
2. Required ARM datastreams
3. Maturity of the algorithm (e.g., research-level to operational)
4. Complexity to perform the retrieval (e.g., data QC and multiple steps)
5. Personnel skill level needed to perform retrieval (e.g., novice to subject expert)
6. Portability of retrieval from site to site (e.g., how much tuning is needed for each site).

Appendix C lists the hydrometeor and vertical air motion retrieval algorithms presented by the subject experts during the breakout session with subject-expert rankings for each assessment. The assessments provide a "fit for purpose" for each algorithm relative to the hydrometeor regime.

3.4.1 Science Impact

Through discussions between model developers and cloud process experts, a consensus developed that both updrafts and downdrafts are needed in deep convective cores and near the bottom of shallow clouds to understand the mass flux and cloud condensation nuclei (CCN) flux within shallow boundary-layer clouds.

There is also a need for vertical air motions in ice-containing clouds (in particular, convective-driven stratiform shields). The retrieval methods for liquid clouds and ice clouds are similar, with the ice phase being harder to constrain due to unknowns related to ice crystal morphology and properties (e.g., backscattering cross sections, ice crystal fall speeds). For the largest scientific impact, it is recommended to develop methodologies for liquid clouds, including warm boundary-layer clouds and lower portions of liquid-dominated deep convective cores, and use the lessons learned to develop ice-phase retrieval algorithms, where applicable.

3.4.2 Actionable Recommendations

In addition to establishing a TRL for each presented retrieval algorithm (see Appendix C), the following qualitative recommendations are based on the discussions between model developers and subject experts during the workshop. The recommendations are flagged as either "quantify" or "retrieval". The "quantify" recommendations analyze observations and provide additional, quantitative information about the ARM observations that can be used in retrieval algorithms. The "retrieval" recommendations involve algorithms with assumptions that yield new products from the ARM observations. The short-term, mid-term, and long-term correspond to 6, 12, and 24+ months of Full-Time Effort (FTE).

3.4.2.1 Near-Term Actionable Recommendations

1. (*Quantify*) The most often heard recommendation made during the workshop was: **calibrate**. This is because all lidar and radar hydrometeor retrieval algorithms require calibrated backscatter or reflectivity factor to distinguish aerosol and cloud droplet returns. Calibration is especially needed in retrieval algorithms using multiple instrument measurements. In addition, many retrieval algorithms need quality-controlled data sets to remove noise, artifacts, and outliers. Thus, it is recommended that lidars and radars be calibrated at regular intervals (~6 months) using both engineering principles and external reference methods (e.g., disdrometers, corner reflectors, etc.).
2. (*Retrieval*) Typically, retrieval algorithms are developed by individuals working in isolation, or in their own 'silo.' Some algorithms are selected and passed through the ARM review process to produce a VAP. Once the VAP is released, it is very difficult to modify the VAP assumptions or algorithm structure. *To break down silos*, it is recommended that real incentives, with monetary value, be used to form small cross-disciplinary teams that develop one or more vertical air motion retrieval algorithms before those algorithms are passed to the ARM review process. The small teams must contain a model developer, a remote-sensing subject expert, and a data scientist. The responsibility of this small team ends with the transfer of code to the ARM VAP review and generation process.
3. (*Quantify*) The moment-based methods assume that only one hydrometeor type is present in the radar resolution volume. For example, either cloud droplets or drizzle droplets, but not both cloud and drizzle droplets within the same radar resolution volume. If both cloud and drizzle droplets are present in the resolution volume, then the three spectrum moments produced by the current ARM processing (i.e., reflectivity, mean radial velocity, and spectrum width) are biased and do not represent the scattering return from a single hydrometeor type. The magnitude and sign of the biases depend on the intensity of the cloud and drizzle droplet populations. It has been shown that the third spectrum moment, spectrum skewness, can be used to identify when both cloud and drizzle droplets are present. It is recommended that all vertically pointing radar spectra be re-processed to calculate the third (spectrum skewness) and fourth (spectrum kurtosis) spectrum moments.
4. (*Retrieval*) Due to the different scattering properties of cloud droplets, raindrops, and ice particles, different vertical air motion retrieval algorithms are needed for each hydrometeor regime. Algorithms using scanning radar data can produce hydrometeor identifications (HIDs) of storm events before applying specific retrieval algorithms to specific regimes. It is recommended that HID algorithms be developed for vertically pointing radars so that hydrometeor regimes are defined in time-height profiles.

3.4.2.2 Moderate-Term Actionable Recommendations

5. (*Quantify*) Retrieval methods based on analyzing the Doppler velocity power spectra are complex to develop and often require a subject expert to implement. However, spectral-based methods are useful to identify multiple hydrometeor types present within the radar resolution volume. For example, cloud and drizzle droplets can produce two peaks in the Doppler spectrum. If the drizzle has a large enough reflectivity, the two peaks will not overlap, but will be two separated peaks in the spectrum. The current ARM processing will not identify both peaks, but will only identify the dominant peak. It is recommended that a multiple peak finding method be developed to identify multiple peaks in each power spectrum and then estimate the high-order moments (i.e., reflectivity through kurtosis) of each peak.

6. (*Retrieval*) Hydrometeor size distribution and vertical air motion retrieval algorithms are either based on analyzing the spectrum moments or based on analyzing the spectra. Moment-based algorithms require more assumptions on the shape of the hydrometeor size distribution, but they are faster and easier to implement than spectral-based algorithms. It is recommended that previously published moment-based algorithms (see Appendix C for possible algorithms) be developed within the ARM ecosystem.

3.4.2.3 Long-Term Actionable Recommendations

7. (*Retrieval*) Spectral-based retrieval methods require fewer assumptions than moment-based methods. It is recommended that previously published spectral-based algorithms (see Appendix C for possible algorithms) be developed within the ARM ecosystem.
8. (*Quantify*) Due to their large areal coverage, coordinated scanning radars have the best chance of estimating vertical air motion in mesoscale convective cores. The retrieval methodology using scanning radars requires multiple processing steps and coordinated efforts to sample the domain with coordinated observations suitable to perform 3D-VAR analyses (using ARM's Three-dimensional Constrained Variational Analysis VAP) and to estimate the 3D wind field. It is recommended to perform Observation System Simulation Experiments (OSSEs) before a field campaign to optimize the radar placement and scanning strategy.
9. (*Quantify*) Previous OSSEs have shown that the time required to acquire data from coordinated scanning radars is critical to the accuracy of convective core vertical air motions retrieved from scanning radar retrieval algorithms. The OSSEs show a significant degradation in retrieval accuracy as the scanning radar update cycle increased from 2- to 5-minutes. A scanning radar using a phased array antenna would be able to sample the domain with a fast update cycle. It is recommended that fast scanning radars using phased array antennas be used in future ARM field campaigns to collect data with very short update cycles.

3.5 Improving Science Impact of ARM Cloud and Precipitation Measurements[6]

To enhance the science impact of ARM cloud and precipitation measurements and capabilities for modeling and scientific research, this session aimed to facilitate discussions on the potential of using ARM capabilities, including observations and LES, to improve understanding and to bridge scales of models and processes. To provide concrete examples for discussions, overviews and needs from a causal discovery study based on ARM data, from LASSO and from THREAD (Tying in High Resolution E3SM with ARM Data), were presented. In general, the session concluded that ARM observational and simulation data sets are useful for improving process-level understanding, for parameterization development, and for ESM evaluation and improvement, and some coordination is needed to facilitate the interactions between sub-specialties.

First, by using nonlinear causal discovery on ARM cloud measurements, intrinsic nonlinear interactions within clouds can be identified and illustrated as multi-variate causal diagrams showing interactions

[6] Author: Po-Lun Ma. Presenters: Peter Jan van Leeuwen, William Gustafson, and Yunyan Zhang.

among meteorological and cloud microphysical drivers. The study highlighted the significance of considering both individual and interactive effects of variables such as effective radius, cloud thickness, and vertical velocity. An important finding was the demonstration of differences between clouds with and without drizzle. Drizzling clouds are more complex, and more data is needed to understand their properties. To conduct this research and identify more factors affecting clouds, high-temporal-resolution data sets are needed.

In addition to causal discovery from data analysis, ARM observations are very useful for evaluating and constraining cloud and precipitation process representations in the kilometer-scale E3SM, also known as Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM). As demonstrated in the THREAD project, model deficiencies in simulating convective mixing, precipitation clusters, ice condensate amount, and diurnal cycle of convection, including shallow-to-deep convection transitions and land-atmosphere interaction, are revealed. Observational constraints based on ARM data may be used directly in model calibration, e.g., the turbulence and cloud schemes. These studies provide insights into model biases and guidance for future model development. Close collaboration between ARM and the ESM communities will be highly valuable.

A unique capability of ARM is the large LES library produced by LASSO. The workflow LASSO established for model initialization has been adopted by the user community. Examples of using LASSO data were discussed, including feature identification, parameterization evaluations, and studies on cloud heterogeneity impacts, among others. Vertical velocities, cloud base mass flux, and cloud microphysics retrievals were identified as key observations that would enhance scientific studies.

Recommendations

1. **Observational needs**: Clouds and precipitation are the net result of many integrative processes in the atmosphere. To simulate clouds and precipitation realistically in models, all the relevant processes need to be represented appropriately so that the precipitation location, timing, intensity, and frequency are simulated correctly for the right reasons. To achieve this goal, key observations that would be helpful for improving cloud and precipitation process representations include cloud macrophysics, cloud population statistics, and in-cloud microphysical properties for stratiform, stratocumulus, shallow cumulus, and deep convective clouds. Useful retrievals include liquid and ice water content, profiles of cloud condensation nuclei and ice nuclei, cloud droplet and ice crystal number concentration profiles, cloud and drizzle properties, cloud water phase partition, and precipitation for an O (100 km) region on a O (1 km) grid. In addition to cloud microphysics properties, hydrometeor classification, vertical velocities below and in cloud, and cloud-base mass flux are useful for understanding cloud macrophysical and radiative properties. Soil state and surface fluxes and their variances across the region are important for land-surface effects on clouds and precipitation. For model evaluation and improvement with better scientific understanding, these data sets are needed at high temporal resolution (e.g., on the order of minutes for macrophysical properties of cloud populations and seconds for cloud microphysical properties and processes).
2. **Benchmark use cases for modeling studies across scales**: Addressing modeling challenges such as sub-grid-scale heterogeneity as well as cloud macro- and microphysical properties requires robust observational data, but inconsistencies exist between data and models of various scales. To bridge the gap, establishing an extensive golden case library for different cloud regimes would be very helpful. Building upon the success of LASSO and THREAD, the large use case library could use consistent use of observational data to create initial, boundary, and forcing data to drive LES, single-column

models, standalone cloud-resolving models including doubly periodic SCREAM (DP-SCREAM) for mechanistic understanding, model physics critique, and error tracing. In addition, high-quality observational data are needed to serve as metrics in model diagnostics, as well as the characteristics of observation uncertainties for the construction of cost function or error matrix during model parametric calibrations. Close collaboration between modelers and ARM data scientists would benefit not only model improvement but also provide insightful guidance on the priorities of data product development and field campaigns.

4.0 Workshop Conclusions

The workshop has aimed to provide actionable recommendations for ARM to advance cloud and precipitation measurements and science. While the discussions were grouped by geophysical variables (e.g., warm rain, solid precipitation, vertical air motion) and specific recommendations were offered, there are common themes in these recommendations, as summarized below.

- For vertical air motion and many cloud and precipitation variables, quantities can be estimated by leveraging various instruments and methods. However, the scientific impact of these products has not been maximized partly due to the following reasons.
  - Most of these advanced products are only available for certain periods and locations, depending on the PI-funded projects. Since some methods may not be ready yet for ARM to produce routine products, building a case library by adding to existing ARM epochs and bundling a set of observations and retrievals can be an intermediate and effective step to enhance the scientific impact of ARM data and products.
  - The differences between retrievals for some variables (e.g., cloud droplet number concentration and air motion) remain too large to be ideal. While the differences are likely due to structural errors that can be assessed through intercomparison, ensuring well-calibrated measurements across all various instruments used in the retrieval is the first step to reconcile the retrieval differences. All retrieval methods should strive to include proper error propagation and incorporate the uncertainty introduced by all possible sources using Bayesian inference techniques. To enhance the product impact, facilitating intercomparison activities and providing documents on retrieval methods that are accessible to non-experts are recommended.
- Strengthening communication and collaboration between retrieval, modeling, and data analytics groups has been a recurring emphasis throughout the workshop. These cross-group discussions are no longer limited to understanding the needs of modelers but now extend to helping modelers recognize and consider parameter and structural errors in retrieval products. While the importance of such collaborations is well recognized and explicitly encouraged in ARM/Atmospheric System Research (ASR) funding announcements, building effective teams remains a challenge due to constraints such as overburdened and misaligned schedules. Having dedicated leadership and focused groups to drive collaborative projects is not a new mechanism, but it remains one of the most effective strategies for fostering these efforts. Ultimately, successful initiatives depend on the convergence of the right research questions, timing, and available expertise.
- There was consensus on the need to explore novel observation strategies for addressing the observational gaps, advancing our scientific understanding, and meeting the evolving needs of modeling development. These include operating advanced instruments such as UAS and new radar

systems to measure upstream conditions and enhance the contextual understanding of cloud systems, expanding the deployment of multiple co-located active remote-sensing instruments, deploying ARM's mobile facilities to under-observed regions, and revisiting and potentially applying innovative approaches such as machine learning techniques to data collection, processing, and integration.

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Appendix A

Workshop Agenda

Day 1: 15 October

Plenary: Overview & Vision			
09.00	Welcome and Workshop Charge	Jim Mather	10
09.10	Workshop Format, Deliverables, Logistics	Christine Chiu & Paytsar Muradyan	5
09.15	Introductions of participants	All	15
09.30	Vision of cloud and precipitation science and measurements	Leo Donner	45
10.15	Break		15
10.30	Programmatic view and vision of C&P science and measurements	Jennifer Comstock	30
11.00	Overview of core C&P measurements	Adam Theisen	30
11.30	Overview of core C&P data products	Damao Zhang	30
12.00	Lunch	Paytsar Muradyan	60
13.00	**Breakout sessions 1 & 2**		180
16.00	Break		15
16.15	**Plenary: Breakout Summary & Recommendation**	All	40
16.55	Day 1 Adjourned		
18.00	Group Dinner		

Day 2: 16 October

08.30	Breakout sessions 3 & 4		180
11.30	Break		15
11.45	**Plenary: Breakout Summary & Recommendation**	All	40
12.25	Lunch	Paytsar Muradyan	60
Plenary: Improving science impact of ARM C&P measurements (Po-Lun Ma)			
13.25	Introduction	Po-Lun Ma	5
13.30	Using nonlinear causal discovery on ARM C&P measurements for process-level understanding	Peter Jan van Leeuwen	15
13.45	Gaps and opportunities for increasing the impacts of LASSO on cloud and precipitation science	William Gustafson	15
14.00	Role and opportunities for ARM cloud and precipitation measurements in high-resolution modeling: Examples from THREAD	Yunyan Zhang	15
14.15	Discussions	All	35
14.50	Break		10
15.00	Discussion on priority	Session Leads	60
16.00	Writing Assignment, timeline and possible manuscript	Christine Chiu	15
16.15	Day 2 Adjourned		

Day 1: 15 October

13.00	**Breakout 1 – Air velocity from bottom to top (Christopher Williams)**		
	Introduction	Christopher Williams	5
13.05	**Science requirements** for process understanding and parameterization developments/evaluations	Greg Elsaesser	30
	Measurement requirements including calibration, core processing, and retrieval methods		
13.35	Lidar	Virendra Ghate	15
13.50	Cloud Radar	Israel Silber	15
14.05	Radar Wind profiler	Paytsar Muradyan	15
14.20	Scanning radar	Mariko Oue	15
14.35	Break		15
14.50	Discussion	All	70
16.00	Break		15

13.00	**Breakout 2 – Solid precipitation at surface (Adam Theisen)**		
	Introduction	Adam Theisen	5
13.05	Essential observables and science requirements for studying precipitation processes and their impacts on energy and water cycle	Sergey Matrosov	30
13.35	Overview of ARM's North Slope of Alaska and Mobile Facility Solid Precipitation Measurements	Adam Theisen	10
13.45	Assessment of NSA Snow Monitoring Arrays	Matthew Sturm	20
14.05	Analysis and Products from Precipitation Imaging Systems	Fraser King	15
14.20	Break		10
14.30	Overview of retrieval methods and uncertainty	Joe O'Brien	15
14.45	Advances in precipitation quantification using machine learning	Fraser King	15
15.00	Discussion on accessibility and opportunity of surface sold precipitation measurements	All	30
15.30	Short-term and long-term development goals	All	30
16.00	Break		15

Day 2: 16 October

08.30	**Breakout 3 – Ice-containing clouds (Israel Silber)**		
	Introduction	Israel Silber	5
	Essential observables and science requirements for ice-containing clouds and their interactions with aerosols		
08.35	From observational perspective	Greg McFarquhar	25
09.00	From modeling perspective	Xue Zheng	15
	Ice microphysical properties		
09.15	Overview of retrieval methods	Israel Silber	20
09.35	Status of radar measurements and possible plans for science requirement	Ya-Chien Feng	20
09.55	Break		10
10.05	Discussion	All	60
11.05	**Next steps and recommendation**	All	25
11.30	Break		15

08.30	**Breakout 4 – Boundary-Layer Clouds (Christine Chiu)**		
	Introduction	Christine Chiu	5
	Essential observables and science requirements for studying boundary layer clouds and their interactions with aerosols		
08.35	From observational perspective	Tianle Yuan	15
08.50	From modeling perspective	Po-Lun Ma	15
	Cloud droplet number concentration and precipitation below clouds		
09.05	Overview of retrieval methods and uncertainty	Christine Chiu	10
09.15	Status of radar and lidar measurements and possible plans for addressing the current issues	Christopher Williams & Rob Newsom	10
09.25	Discussion	All	40
10.05	Break		10
	Surface liquid precipitation		
10.15	Surface precipitation quantification using machine learning	Haonan Chen	10
10.25	Status of ARM surface precipitation measurements	Zeen Zhu	10
10.35	Discussion	All	30
11.05	**Next steps and recommendation**	All	25
11.30	Break		15

Appendix B

Workshop Participants

ARM Facility
Jim Mather

Chair
Christine Chiu

Participants – CPMSG
Jennifer Comstock
Nicki Hickmon
Ya-Chien Feng
Po-Lun Ma
Paytsar Muradyan
Joseph O'Brien
Rob Newsom
Alyssa Sockol
Adam Theisen
Dié Wang
Christopher Williams

Participants (in-person) – External Invitees
Leo Donner
Greg Elsaesser
Virendra Ghate
Siddhant Gupta
William Gustafson
Fraser King
Greg McFarquhar
Mariko Oue
Israel Silber
Tianle Yuan
Yunyan Zhang
Xiaojian Zheng
Xue Zheng

Participants (remote) – External Invitees
Haonan Chen
Scott Giangrande
Peter Jan van Leeuwen
Sergey Matrosov
Julia Shates
Matthew Sturm
Damao Zhang
Zeen Zhu

Appendix C

Vertical Air Velocity Algorithm Recommendation Matrix

This appendix describes the technical readiness level of several vertical air velocity algorithms discussed during the workshop. Developing a product within the ARM ecosystem requires many procedural steps and associated challenges. Focusing on **Actionable Recommendations**, the algorithms are reviewed and scored based on the effort to proceed from their current state to the level just before handing the code to ARM infrastructure to produce an ARM process-controlled VAP. This level of readiness may be considered a “PI product”, except that the development is performed using ARM resources (i.e., ARM datastreams, ARM personnel, and ARM computers).

In Table C3, the rows correspond to different algorithms and the columns provide either descriptions or numerical values. The rankings and numerical values were generated by the subject experts involved with the workshop. Numerical values are relative scores with low scores representing ‘easy’, or a low hurdle, and high values representing ‘hard’, or a higher hurdle. The algorithms have been listed in rank order, from lowest to highest normalized score (i.e., from easiest to hardest to implement). Additional information for each column is provided in Tables C1 and C2.

Table 2. Explanation of descriptive headers in Table 4.

Header	Description
Number	Algorithm reference number
Name	Description name of algorithm
Cloud Regime	Hydrometeors detected by the ARM instrument, including aerosol, clouds droplets, drizzle droplets, raindrops, ice particles, aggregates, rimmed particles, graupel, and hail.
Methodology	Brief description of the algorithm method
Science Need	Brief description of the science need addressed by the final products
Additional Products	Additional products, in the addition to vertical air velocity, produced by the algorithm
Issues/Constraints	Known issues or constraints of the algorithm
ARM Assets	List of ARM instruments needed to collect the data used in the algorithm
Data Level	Data level of the ARM datastream produced by the ARM assets

Table 3. Explanation of numerical headers in Table 4.

Header	**Description**
Maturity	What is the maturity of the algorithm? 1 = very mature with publications 2 = some maturity, PI product 3 = not mature, proof of concept
Developer	How much of a Subject Expert does the developer need to be to develop the algorithm? 1 = novice, no instrument knowledge 2 = intermediate, some instrument knowledge 3 = advanced, a lot of instrument knowledge
Time/ Effort	Using the specified Developer, how much time, or effort, is needed to get the algorithm implemented at one ARM site? 1 = approximately 6 months (FTE) 2 = approximately 12 months (FTE) 3 = approximately 24 months (FTE)
Portability	How hard would it be to translate the algorithm developed at one ARM site to another ARM site? 1 = easy to port 2 = some effort is needed to port 3 = difficult to port
Normalized Score	Total score normalized by the maximum possible score Minimum score = 4/12 = 0.33 Maximum score = 12/12 = 1.0 0.33 <= Easy Effort < 0.58 (lowest third) 0.67 <= Moderate Effort < 0.75 (middle third) 0.83 <= High Effort < 1.0 (highest third)
Color Coding	Cells are color coded based on numeric value Green = 1 and lowest third of Normalized Score Yellow = 2 and middle third of Normalized Score Red = 3 and highest third of Normalized Score

Table 4. Effort to advance a retrieval product to the pre-VAP stage with algorithms listed in rank order.

Number	Name	Cloud Regime	Methodology	Addresses Science Need	Additional Products	Issues / Constraints	ARM Assets	Data Level	Maturity	Developer	Time/Effort	Portability	Norm. Score
A.1	Doppler Lidar in clear air	aerosol backscattering, no hydrometeors present	Aerosols are assumed to be passive tracers so that aerosol motion is equal to air motion.	Clear air turbulence statistics and TKE dissipation rates can be derived.		Sample volume must be free of insects and hydrometeors.	DL	b1 VAP	1	1	1	1	0.33
A.2	Cloud droplets as tracers	Cloud droplets	Use cloud droplets as tracers with assumed small fall speed	Air motions within liquid cloud droplet regime		Need to identify regions only with cloud droplets. The presense of drizzle drops will cause errors.	MWACR KAZR W-SACR (vertical pt)	Moments a1	1	2	2	2	0.58
A.3	Air Motions from single RWP observations	Raindrops, ice particles, aggregates, graupel	For each identified hydrometeor regime, use a Z-Vmean relationship to convert observed Z to hydrometeor fall speed, and air motion is the difference from the observed radial velocity.	Air motion in moderate to heavy rain rates and in convective cores.		Need to classify precipitation regions to assign Z-Vmean to each region.	RWP	Moments a1 b1	1	2	2	2	0.58
A.4	2D air motion at high elevations using scanning radar RHIs	Rain, drizzle, and snow	Estimate vertical air motion from single Doppler radar RHI measurements.			Need to remove hydrometeor fall speed from measured Doppler radial velocity. Large errors at lower elevation angles (<~45 degrees).	C-SAPR	Moments a1 b1	2	2	2	2	0.67
A.5	Mean velocity difference at two radar wavelengths	Rain drops	Difference in radial velocity at two different radar wavelengths enables DSD and air motion estimate.	Air motion and DSD in moderate rain rates.	Raindrop size distribution and air motion	Need to have rain rates greater than ~3mm/hr so that larger raindrops are present to cause differences in measured Doppler velocity spectra.	KAZR and RWP	Moments a1 b1	2	2	2	2	0.67
A.6	Upper Edge of Doppler Velocity Spectra - Supercooled Drizzle Droplets	Supercooled Drizzle Droplets	Identify the must upward portion of the Doppler velocity spectrum and correct for turbulent spectrum broadening effects.	air motion in supercooled drizzle droplets		Need to classify cloud to identify supercooled drizzle droplets to assign proper fall speed relationships.	KAZR	Moments a1	2	2	2	2	0.67
A.7	Lidar/Radar during Drizzle	Drizzle droplets	Derive drizzle size distribution and vertical air velocity using data from two of the 3 instruments; ceilometer, Doppler Lidar and KAZR.	Quantification of drizzle DSD and air motion	Drizzle DSD	Sample volume contains only drizzle drops below cloud base with no ice crystals	DL Ceilometer KAZR	Moments b1 VAP	1	3	2	3	0.75
A.8	Upper Edge of Doppler Velocity Spectra - Cloud Droplets	Cloud droplets	Identify the must upward portion of the Doppler velocity spectrum and correct for turbulent spectrum broadening effects.	air motion in liquid cloud regimes		Need to be observing liquid cloud droplets so that smallest particle is assumed to have zero fall speed.	KAZR	Spectra a1	2	3	2	2	0.75
A.9	Spectrum differences between two radars at different wavelengths	Raindrops, ice particles	Similar to A.5, except use the Doppler velocity power spectra to fit DSD at different wavelengths.				KAZR RWP MWACR	Spectra a1	2	3	3	2	0.83
A.10	Scanning 3D-Var	Rain, drizzle, snow, graupel, hail	Estimate vertical air motion from multi-Doppler radar measurements using a 3D-Var technque.	Vertical and horizontal wind motion in convective cores.	Hydrometeor classification, rainfall rates	Mass continuity, hydrometeor fall speed, and precip. patial distribution must not change within a sampling time (generally 5 min).	C-SAPR	Moments a1 b1	2	3	3	3	0.92
A.11	Multiple lidar and radar constrained retrieval	Multiple ice particle habits	Combine multiple observations using Bayesian framework to retrieve ice habit and size distributions.	Identify ice habits and regimes			KAZR DL HSRL	Moments a1	2	3	3	3	0.92
A.12	Mie Notch in Doppler Velocity Spectra	Rain drops	Identify the Mie notch in 1.7 mm diameter raindrops in W-band Doppler velocity power spectra.	Vertical air motion in light stratiform rain	Raindrop size distribution	Retrieval limited to light rain rates (<3 mm/hr) due to attenuation of W-band signal in heavier rain.	MWACR W-SACR (vertical pt)	Spectra a1	3	3	3	3	1.00

Algorithm References

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