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

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Executive Summary

This report sets forth the outcomes from a first workshop of the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility's Clouds and Precipitation Measurements and Science Group (CPMSG).

The workshop was structured around seven strawman recommendations to ARM infrastructure that had been drafted based on internal and external inputs gathered since the CPMSG's inception in March 2019.

The chairs of the DOE ARM cloud-related working groups and several external science and infrastructure attendees were invited to assist in meeting workshop goals.

The objectives of the workshop were:

- Openly consider whether or not to advance each recommendation in a final report (or add other recommendations)
- Gather additional input re implementation or other issues
- Test a matrix-based strategy for gathering community input on proposed new investments.

Reports from each session are appended and key recommendations have been extracted from those reports.

As discussed at the close of the workshop, general findings from the meeting were presented at the ARM/Atmospheric System Research (ASR) annual science meeting.

The next step will be to develop actionable strategies around recommendations and a transparent process for identifying community needs.

Acronyms and Abbreviations

2D	two-dimensional
3D	three-dimensional
4D	four-dimensional
ACT	Automated Compliance Tooling
ADI	Analog Devices, Inc.
AERI	atmospheric emitted radiance interferometer
AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
ARSCL	Active Remote Sensing of Clouds
ASR	Atmospheric System Research
CACTI	Cloud, Aerosol, and Complex Terrain Interactions
CALIPSO	Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAUSES	Cloud Above the United States and Errors at the Surface
CCN	cloud condensation nuclei
CCNPROF	Cloud Condensation Nuclei Profile
CFMIP	Cloud Feedback Model Intercomparison Project
CHARMS	Combined HSRL and Raman lidar Measurement Study
CIRC	Continuous Intercomparison of Radiation Codes
CLOWD	Clouds with Low Optical (Water) Depths Working Group
COSP	CFMIP Observation Simulator Package
CPMSG	Cloud and Precipitation Measurements and Science Group
DL	Doppler lidar
DOE	U.S. Department of Energy
DOI	Digital Object Identifier
DQO	Data Quality Office
ENA	Eastern North Atlantic
GASS	GEWEX Atmospheric System Studies
GCM	global climate model
GCSS	GEWEX Cloud System Study
GEWEX	Global Energy and Water Exchanges
HSRL	high-spectral-resolution lidar
IOP	intensive operational period
ISDAC	Indirect and Semi-Direct Aerosol Campaign
LAFE	Land-Atmosphere Feedback Experiment
LASSO	LES ARM Symbiotic Simulation and Observation

LDRD	Laboratory Directed Research and Development
LES	large-eddy simulation
LWP	liquid water path
MBL	marine boundary layer
M-PACE	Mixed-Phase Arctic Cloud Experiment
MPL	micropulse lidar
MWR	microwave radiometer
MWRRET	Microwave Radiometer Retrieval
NASA	National Aeronautics and Space Administration
NDROP	Droplet Number Concentration
NOAA	National Oceanic and Atmospheric Administration
NSA	North Slope of Alaska
PBL	planetary boundary layer
PI	principal investigator
PSD	particle size distribution
Py-ART	Python ARM Radar Toolkit
QVP	quantified value proposition
RACORO	Routine ARM Aerial Facility CLOWD Optical Radiative Observations
RFMIP	Radiative Forcing Model Intercomparison Project
RL	Raman lidar
RWP	radar wind profiler
SEUSA	Southeast U.S.A.
SFA	science focus area
SGP	Southern Great Plains
SHEBA	Surface Heat Budget of the Arctic Ocean
SNR	signal-to-noise ratio
TBS	tethered balloon system
TKE	total kinetic energy
TRACER	Tracking Aerosol Convection Interactions Experiment
UAS	unmanned aerial system
UEC	User Executive Committee
VAD	velocity-azimuth display
VAP	value-added product
VARANAL	Variational Analysis
VPT	vertically pointing
WMO	World Meteorological Organization

Contents

1.0 Background

ARM's Clouds and Precipitation Measurement and Science Group (CPMSG) was chartered in March 2019 to help ARM "improve the performance and science impact of the ARM measurements of clouds and precipitation" (https://www.arm.gov/about/constituent-groups/cpmsg-group). To achieve this, the group is designated to include a combination of representatives of science areas associated with cloud and precipitation measurements and representatives from ARM including technical points of contact for relevant ARM instruments, the Data Quality Office, and leads for data product development.

The group began meeting in the spring of 2019 with initial goals of identifying community needs and engaging with the science community during the June ARM/ASR joint meeting. The core question considered by the group was: What are scientific areas where barriers exist for ARM to support science advances most effectively, and do we see ways that any of those barriers might be addressed to enable progress? Discussions in the group quickly organized around a set of meteorological regimes where ARM observations were considered to offer unique advantages for scientific progress:

- High-latitude including mixed-phase and ice processes
- Convection
- Cirrus
- Boundary-layer structure including land interactions
- Shallow warm clouds.

At the June ARM/ASR meeting, the CPMSG hosted a breakout session to collect input from the community around these, and possibly other, areas. A number of needs were identified at that session and through other engagement with scientists at the June meeting, including both specific measurements as well as more general capabilities such as supporting open-source software development to facilitate the implementation of retrieval codes.

In the months following the spring meeting, the CPMSG met several times virtually to review and organize the information that had been collected. These discussions led to the consolidation of input into a set of barriers and a set of enabling capabilities. The barriers were all needs or issues that were suggested as obstructing ARM's ability to more effectively advance science themes while the enabling capabilities were all inputs that were suggested as potential avenues to help to mitigate various barriers (see Appendices A and B). From these two lists, which were compiled without bias from all sources, seven strawman recommendations were developed as potential programmatic strategies for lowering barriers to progress:

1. Develop and maintain a public list of measurement or analysis gaps that require specific additional investments or integration.
2. Create a "short-term measurement" designation and strategy for instrument and data product streams that are too resource-intensive to bring into ARM's legacy, long-term measurement paradigm with sufficient consistency.
3. Develop and maintain a public list of measurements or datastreams that are getting insufficient use to warrant further investment.

4. Develop and implement a plan to reduce particularly high-volume datastreams while maintaining scientific value.
5. Develop and maintain a system of regime classification for long-term data sets and deployments of ARM mobile facilities.
6. Develop and support an open-source and community code paradigm for existing and future data products and tools.
7. Seek and support frameworks that bring individuals and groups together for limited joint exercises.

Where recommendation 1 suggests a strategy to identify new marginal investments with the greatest potential impact via ongoing community input, recommendations 2–4 suggest strategies for streamlining existing investments, and recommendations 5–7 suggest strategies for increasing the impact of existing investments.

With the input from the community organized in this way and the seven strawman recommendations in hand, the CPMSG began planning a workshop. The purpose for the workshop was to advance the topics raised over the past year toward actionable strategies and to outline a framework that will help ARM to continue to develop priorities and associated strategies beyond this workshop.

The workshop was planned from the outset as a virtual meeting and was held on March 23-24. The meeting was organized around the three ASR cloud-oriented working groups, which were well aligned with the meteorological themes that had developed in group discussions. An overview of the meeting and key recommendations are provided in the next section.

2.0 Discussion and Outcomes

The workshop agenda (Appendix C) was organized into a series of joint plenary and parallel breakout sessions over two days. One breakout session was dedicated to each of recommendations 2–7 and three breakouts were dedicated to considering recommendation 1 within each of the cloud working group areas (mixed-phase and ice processes, boundary-layer structure and shallow cloud microphysics, and convection and cirrus). The detailed findings of the resulting nine breakout sessions are contained in the breakout reports (Appendix D). Here we make a brief synopsis.

Perhaps the most important outcome of the workshop was that all of the seven recommendations going into the workshop were confirmed as warranting further consideration. At the end of the meeting, the group considered omitting a recommendation for regime classification, and potentially adding a recommendation regarding integration of ARM and ASR resources, but decided against those changes. The more specific outcomes of the workshop can therefore be divided into the seven recommendation areas.

For **Recommendation 1** (a public list of measurement or analysis gaps), the group dedicated three breakout sessions to testing a science traceability matrix approach (similar to that of the National Aeronautics and Space Administration [NASA]) for identifying gaps within the existing ARM/ASR cloud-related working groups. The main concept is simply that science traceability matrices would be required as supporting material to each item proposed for new investment by the facility, and those proposed investments would be listed publicly with the supporting material (science traceability matrix) being accessible alongside each. The following general themes emerged from these three breakouts (see breakout reports 1a, 3a, and 4a in Appendix D):

- Matrix elements should include motivating science questions (whether within the matrix or above it), problems/roadblocks, impact/importance, solutions/recommendations (the marginal investment being suggested), and readiness/maturity (similar to National Oceanic and Atmospheric Administration [NOAA]'s), as well as a roadmap to modeling goals.
- Overlap between working groups on matrices are expected and would be fine, but perhaps warrant identifying a lead for each recommendation (e.g., one working group co-chair).
- Separation of topics, e.g., clear-sky boundary layer versus boundary-layer clouds (as initially identified by the committee) was considered better replaced by a more holistic approach to combined science areas.
- The breakout groups practiced filling out matrices and emerged with some specific recommendations, finding the process generally fruitful and resulting in strawman matrices that can be suitable for consideration by the full working groups if this approach is pursued.
- The last group to meet ended up mapping a full host of near-, mid-, and long-term priorities based on the process (see Report 4a), which can perhaps be considered some testament to the potential power of the approach.

The other strawman recommendations were fleshed out in the remaining six breakouts, with the following general outcomes:

Recommendation 2 (short-term measurement designation; Report 3b)

- This is an important new approach for ARM to pursue owing to likely benefit to scientific outcomes.
- However, special modes of operation should not compromise high-quality, calibrated products and the access to decision-making regarding operational modes should be fair and equitable (care to avoid "insider" principal investigator [PI] access).
- A strawman proposal for how to structure access would be required to move forward, including appropriate review and outreach, and various important considerations were identified.

Recommendation 3 (capabilities review, Report 2a)

- ARM already has a proposed process for reviewing and retiring capabilities, which was reviewed in this workshop breakout.
- Suggestions included adding a comment period for user feedback on proposed retirements and considering reviews on a site-specific basis.

Recommendation 4 (high-volume data reduction, Report 4b)

- We acknowledged that radar and especially lidar Doppler spectra represent logistical challenges in terms of both bandwidth and storage, resulting in data that is uniquely useful for some science applications but currently garners relatively few users.
- Potential solutions included saving for selected conditions, modifying the ingest to improve efficiency, and performing some onsite processing to reduce bandwidth demand.
- Convening a focus group could be helpful to advance strategies.

Recommendation 5 (regime classification, Report 1b)

- We agreed that ‘regime’ breakdowns could serve to encourage the more frequent use/download of ARM datastreams, wherein low use/download has often been attributed to ARM user difficulty in discovering key cloud events or identifying the most useful/calibrated ARM data sets.
- A short-term goal would be to identify overlaps of core ARM value-added products (VAPs), whereas longer-term goals could include cloud type classifications for long-term sites and campaigns.

Recommendation 6 (open source and community code, Report 2c)

- ARM is already moving towards more open-source software for a variety of purposes (e.g., the Python ARM Radar Toolkit [Py-ART], Automated Compliance Tooling [ACT], and Analog Devices, Inc. [ADI]), and there is wide support for that trend.
- Educating users both within and outside of the facility would be highly beneficial.
- Associated software development is needed to help users get at the information they need without downloading entire data sets.

Recommendation 7 (joint exercises, Report 2b)

- We agreed that stimulating joint community exercises could increase ARM’s reach and impact (as demonstrated historically), and that annual PI meetings provide a natural opportunity to initiate and shepherd activities.
- Stimulation of group activities should be driven from the modeling side, but also from the point of specific scientific foci, and observational objectives.

3.0 Conclusion and Next Steps

The first CPMSG workshop provided an analysis and distillation of ideas that had been pursued by the group during its first year. These ideas were the product of discussions within the group and with members of the ASR community. The last session of the workshop identified next steps including communication of recommendations, first through the annual ARM/ASR joint meeting and then through a workshop report.

One of the significant outcomes from this workshop was the development of a strawman matrix approach for identifying and characterizing community needs in a transparent way. A follow-on action from this workshop will be to refine and implement this process.

The identification of needs and strategies at this workshop helped to foster recommendations for how ARM can better serve the cloud and precipitation science community in particular and was part of a larger effort to collect input to update ARM’s decadal vision, which addresses how ARM can better advance its mission.

As the decadal vision document is finalized, we expect that the CPMSG will engage to integrate the ideas coming out of this workshop and those that are captured in the decadal vision to develop specific actionable strategies for advancement. As with the process leading up to this workshop, that work will involve active engagement of this group with the larger community.

Appendix A

Aggregated Barriers

In its first months of existence (spring of 2019), the CPMSG set out to identify areas where ARM could improve its service to the science community and barriers to science progress. This appendix captures an aggregation of input collected from the CPMSG and the broader ASR community, through a breakout session at the 2019 ARM/ASR spring meeting and follow-on discussions with the ASR working group chairs later that year.

Summary of overall objectives from our charter (https://www.arm.gov/publications/programdocs/doe-sc-arm-19-001.pdf):

- The CPMSG is charged with working together to provide constructive recommendations regarding the operation, characterization, and development of instruments providing cloud and precipitation measurements along with the development of data products derived from these instruments and the identification of measurement gaps.
- A driving consideration for the group should be how resources can best be applied to measurements of cloud and precipitation properties and the development of associated data products to increase the scientific impact of these measurements.

Potential Barriers to Progress

1. Boundary-layer structure and near-cloud dynamics:
    a. Coastal and island locations may not be ideal, but multiple locations are a strength
    b. Planetary boundary-layer (PBL) height and structure are difficult to robustly define
    c. Need other parameters to describe internal PBL structure
    d. Complementary data sets can be difficult to harmonize
    e. As we look at older data, we will not have access to newer instruments – a factor in assembling these site climatologies
    f. 3D structure and spatial context are important on the km scale
    g. Marine boundary-layer (MBL) analysis at ARM's Eastern North Atlantic (ENA) observatory requires ocean surface properties.
2. Shallow warm-cloud precipitation formation and structure:
    a. Lack of robust droplet number concentration retrievals (column average adequate?)

   b. Large-scale tendencies variable, difficult to constrain
   c. Location-specific limitations (Oklahoma consistently high-aerosol, North Slope of Alaska (NSA) cloud condensation nuclei (CCN) data quality? ENA poorly coupled?)
   d. Scanning is important
   e. Multi-frequency is important
   f. Ceilometer backscatter profiles could be calibrated to give rain rate
   g. Aerosol measurements are important
   h. Will aerosol remote-sensing data be validated?
   i. Aerosol, cloud and precipitation must be measured well at the same time
   j. Significant advances with shallow clouds – e.g., with the quality and number of large-eddy simulations (LES) but still run into problems with LES microphysics
   k. Limits to microphysical retrievals challenge to models, but Rob argues that the Droplet Number Concentration (NDROP) VAP is useful and Ann suggests that providing Christine’s retrievals or other PI products with a merged data set could help move things forward.

3. Mixed-phase cloud properties and processes:
   a. Hydrometeor phase evaluation in climate models requires forward simulation approach and unique processing of multiple data sets
   b. Global climate mode (GCM) forward simulators such as the Cloud Feedback Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP) are often problematic
   c. Use of COSP with satellite measurements does not face the spatiotemporal scale differences that arise when using ARM measurements to evaluate GCMs
   d. This is a topic of great interest to GCMs, but what can ARM actually provide?
   e. COSP is very widely used and ARM can contribute to improving such tools
   f. It is a non-trivial task to combine even lidar and zenith radar for optimal comparisons; recommend open source code for transparency, flexibility
   g. Multi-wavelength zenith radar observation strategy (sensitive to cold-cloud properties; powerful overlap with future spaceborne remote sensing)
   h. Mixed-phase clouds are common at ENA in the winter in post-frontal situations above about 1 km, not so different from conditions seen in the Southern Ocean.

4. Ice properties and processes:
   a. Key instruments for robust analyses have not been collocated for long periods
   b. Issue with comparing diversity of microphysical habit in models with single HID
   c. Scanning strategies that serve science needs are important

   d. Comparison with airborne particle size distribution (PSD) measurements is necessary, challenging
   e. Ice properties and processes are responsible for model diversity
   f. Confidence flag would be valuable for ice cloud retrievals.

5. Coupled dynamics and microphysics of deep convection:
   a. Integration of modeling and multi-instrument 4D data sets is a large effort
   b. Multi-doppler wind and microphysical property retrievals are not yet very well vetted
   c. Rapid scanning requires supervision or automated tracking
   d. Lots of new information is available in rapid scan modes that is not yet known
   e. Tension between long-term standard operations and intensive operational period (IOP) mode
   f. Doppler lidar in very simple mode can be used better
   g. Add observation of 3D thermodynamic environment of clouds
   h. Add vertical profiles of aerosol
   i. Add disdrometer networks
   j. Not clear how to make use of data for process-level mechanistic understanding
   k. Forward simulators are useful
   l. Epochs could play a role.

6. Cirrus dynamics and microphysics:
   a. Vertical wind speed retrievals not yet operational
   b. Micropulse lidar (MPL) has been a workhorse, need to think about lidar modernization strategy.

7. Other factors:
   a. Scientific topics, measurements, instruments
   b. Cloud organization
   c. Vertical profiles of CCN
   d. Doppler lidar spectra
   e. Microwave radiometer (MWR) that measures under raining conditions
   f. It would be useful to have a regime classifier
   g. Use of measurements beyond radar to study 4D cloud evolution
   h. Integration of satellite and other data sets (e.g., significant potential in combining Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) with ARM measurements at various sites as others have done).

i. VAPS:

    i. Running a VAP for only part of the time does not save much effort once it is developed
    ii. If VAPs were designed differently so as not to deal with all situations, would that save effort and simplify VAP operations?

j. PI data products:

    i. Long time gap between availability of limited science-grade retrievals and usable long-term VAPs, e.g., drizzle at ENA
    ii. PI products not currently required as part of ASR grants, even in the data-oriented calls
    iii. Could consider both PI products and distribution of open-source PI code, but still have some of the same issues with the code because as with the data, the reward for sharing the code is not there yet.

k. Programmatic considerations:

    i. Too many datastreams, not enough staff
    ii. Need simplified access to ARM data, especially large data files (e.g., radar) by allowing data to be preprocessed prior to download (currently possible on ARM shared computing clusters Stratus and Cumulus but future demand could present a problem)
    iii. PI-focused funding approach forces progress into disconnected bits; would it be possible to fund PI teams?
    iv. Science contributions are not just about large-scale model evaluation and development, but also about fundamental scientific advancement.

Appendix B

Strawman Recommendations

The collection of barriers to science progress (Appendix C) involved a long list of issues. The next step in the work of the CPMSG was to organize these issues into broader themes. Those themes are identified here in this set of strawman recommendations to ARM. These broader themes provided the structure that was used to plan the 2020 CPMSG workshop that is summarized in the main body of this report. Barriers that could be fully or partially addressed are listed after each recommendation.

Prioritizing New Investments

- **Develop and maintain a public list of measurement or analysis gaps that require either specific additional investments or integration of PI or external data sets or codes, as well as a method for gauging community support.** The ARM facility's organizational structure of working groups is intended in part to enable its scientific communities to develop consensus recommendations and make them heard. Maintaining a public short list of established needs would enable programmatic and proposer responses based on an agreed-upon foundation. Recommended candidates for this list include microwave radiometers capable to measure liquid water path (LWP) under raining conditions, ocean surface properties at the ENA site, aerosol or CCN profiles, droplet number concentration retrievals, regime-classification algorithms, open-source and community codes for important but difficult analyses (such as forward-simulation of observables from model outputs and 4D analysis of observed or simulated convective structural properties), and multi-wavelength zenith Doppler radar measurements (for synergy with current and future remote-sensing data). Since the incremental investments required and logistical factors are expected to vary widely, we recommend developing a simple system to be used by all working groups for rating all items and proposing new ones. No system will be perfect, but a simple system that is implemented annually could help increase transparency and gauge consensus. (1.6–7, 2.1, 3.1–5, 5.1, 5.10–11, 6.2, 7.1.2)

Enabling Program Capacity

- **Create a "short-term measurement" designation and strategy for instrument and data product streams that are too resource-intensive to bring into ARM's legacy, long-term measurement paradigm with sufficient consistency.** ARM was founded with a leading objective of making long-term measurements, but short-term intensive operational periods (IOPs) were always envisioned at the long-term sites and ARM mobile facilities later made the same long-term measurements at temporary sites. However, as the facility has continually expanded, some instruments and datastreams have turned out to require so much maintenance, expense, labor or other support that it has become practically impossible to add them to the long-term legacy group. We recommend to explicitly establish a class of instruments that are not expected to achieve continuous operation. Some scanning radars would be expected to fall into this class. Instruments released from the demands of long-term data collection would also be freed to pursue more flexible operations, including varying scan strategies, integration time, or other relevant aspects. Decisions would be made on a case-by-case basis, with an eye to maintaining a balance between marginal investment and added value. (1.6, 2.4, 2.5, 4.1, 4.3, 5.1–5.5, 5.6, 5.12, 7.2.2, 7.4.1–2, E.2–6)

- **Develop and maintain a public list of measurements or VAPs that are getting insufficient use to warrant further investment.** ARM datastreams currently number in the hundreds. A fraction of these receive sparse use and do not contribute to higher-level VAPs such as “best estimate” products. The facility has already made significant investment in many cases, yielding data sets that will remain available via the ARM Data Center. However, the marginal value of additional investment appears low. These least-used products, especially when they are relatively expensive to support, can be slated for cessation in order to help make way for new investments that have been identified as particularly high priority by a broad segment of the user community.
- **Develop and implement a plan to reduce particularly high-volume datastreams while maintaining scientific value.** Some instruments are hampered by the very richness of their datastreams. One example is the Doppler radar, the detailed spectral features of which contain a plethora of information about liquid and ice processes. It is not yet obvious to what degree such spectra can be reduced to their moments or other simple properties without loss of valuable information for some use or another. One strategy for handling such data could be to save complete spectra only when some target conditions are present (e.g., mixed-phase, warm or cirrus clouds); use of standard regimes (see below) could be integrated in such decisions. Another strategy could be to save such complete data only when a complete set of complementary data are available (e.g., MWR). Past archives could also be selectively reviewed. A dedicated effort is recommended to identify such datastreams and engage the community in vetting case-by-case recommendations. (7.1.3, C.3, D.2, E.6)

Enabling Usage of Existing Datastreams

- **Develop and maintain a system of regime classification for long-term data sets and deployments of ARM mobile facilities.** In addition to “best estimate” products, ARM has developed the concept of “data epochs” to clearly delineate periods of the most consistently high-quality integrated datastreams. To further enable scientific use of these long (and sometimes large) data sets, we recommend developing and implementing suitable methods of regime classification. We recommend asking working groups for suggestions for simple classification methods, which many PIs have likely already developed for their own uses. If an open-source and community code approach is employed, algorithms can be readily modified for specific purposes. We recommend choosing several simple methods that can be implemented relatively rapidly for beta testing. These could include first-order estimates of 3D structure, e.g., from radar for determining when quantified value proposition (QVP) analyses are most robust or particular PBL conditions prevail. Real-time regime classification has already been implemented for limited instruments at SGP and could also be integrated with radar scan strategies or VAP implementation, for instance. (1.6, 3.8, 5.3, 5.10, 7.1.1, 7.2.2, 7.4.2, 7.4.4, C.3, D.1–2, E.5–6)

- **Develop and support an open-source and community code paradigm for existing and future data products and tools.** We recommend leveraging ARM's computational resources and open-source and community code experience (e.g., Py-ART) to enhance user capabilities to effectively harness ARM data and tools. Limited facility support for such code development could help individual PIs or teams work on data sets for specific objectives (e.g., diurnal PBL characterization).
  - **VAPs.** A common barrier to scientific progress is the difficulty of harmonizing multivariate data into "one size fits all" integrated datastreams. ARM's "best estimate" data products have gone far to fit many users. We recommend leveraging ARM's computational resources and open-source and community code experience (e.g., Py-ART) to enable users to take an existing VAP code, alter assumptions, add their own datastreams, and reprocess. Such a capability would allow users to generate and share bespoke "best estimates +" that include PI data products, collocated satellite data, or other additions that fill key gaps for particular applications. Appropriate changes to the "best-estimate" spatiotemporal sampling could be implemented at the same time, yielding datastreams with capacity to overcome barriers with varying approaches in varying sub-areas—no need for one size to fit all. Community examples where user-integrated multivariate data sets have "gone viral" provides impetus. (1.2–1.5, 2.1, 2.6, 2.9, 2.11, 3.6, 7.1.7, 7.2.1–2, 7.3.1–3, 7.4.1–4, A.1–5, B.2–5, D.1–2)
  - **PI data products.** ARM has handled the gap between instrument datastreams and well-accepted VAPs by creating the specific class of datastreams known as PI data products. These are supported by individual PI grants and are generally limited to particular sites and time periods. The effort required for ARM to make these operational at all times and all sites is a major barrier that can be overcome only with sustained investment. We recommend implementing a system in which PI data products are run on ARM computational resources prior to archiving, using open-source and community code standards. This could significantly lower the barrier between PI data products and VAPs, furthering benefit from ARM investments in both datastreams and retrievals. (2.1, 2.11, 4.6, 5.8, 6.1, 7.1.1–2, 7.1.5–6, 7.3.1–3, 7.4.3, B.1, C.1–4)
  - **Forward-simulator codes for climate and mesoscale models.** Forward-simulation tools for comparison of model output directly with observable quantities (rather than with retrievals from those observations) have become increasingly widely used by the climate modeling community in order to use satellite measurements more effectively, especially from active instruments, such as lidar and radar. However, climate model schemes for mixed-phase microphysics, and their implementation within stratiform, convective, and unified schemes, are becoming more rather than less diverse. Furthermore, mismatch between model assumptions and simulator options are already an acknowledged barrier to progress. In the mesoscale modeling community, efforts arguably tend more towards incremental model development that will tend to improve forward simulation skill (e.g., addition of mixed-phase particles). Given increasing model diversity and sensitivity of results to the model-simulator interface, we recommend that ARM seek to support open source and community code from diverse users, who can best optimize codes for their own use—and then share those advances in a flexible framework. (3.1–3.7, 4.5, 5.1, 5.11, B.5)
- Seek and support frameworks that bring individuals and groups together for limited joint exercises. Model intercomparison studies have historically engaged large groups of international scientists around ARM data sets, both long-term and IOP data. We recommend actively seeking additional means of engaging both funded and unfunded researchers in joint activities. One such means could be

around production and use of unique integrated data sets, e.g., via limited programmatic support for community code for bespoke “best-estimate +” data sets to which multiple PIs might contribute PI products or analyses, such as for clear-sky PBL thermodynamic and turbulent structure. Another such means could be led from the climate modeling community within ARM and ASR or other groups, coalescing around specific areas of joint interest where ARM data set mining could make a unique contribution to model evaluation or development. (3.2–6, 4.5, 5.1, 5.10, 7.1.7, 7.4.3–4, A.1–5, C.1–2, C.4)

Appendix C

Workshop Agenda

Monday, March 23

11:00–12:15 ET – Opening Plenary #1
- Virtual meeting orientation (Jennifer, 15 min)
- Introduction/why we're here (Jim, 10 min)
- Summaries of each topic (Ann, 20 min)
- Discussion (30 min)

12:15–12:30 ET – Short break and login to Zoom breakouts
12:30–2:00 ET – Breakout #1
- Mixed-phase and ice processes
- Regime classification

2:00–2:30 ET – Long break
2:30–3:30 ET – Breakout #2
- Open source and community codes
- Capabilities review
- Joint exercises with ARM data

3:30–5:00 ET – Plenary #2
- Breakout summaries (10 min each = 50 min)
- Discussion/how are we doing? (Ann, 40 min)

Tuesday, March 24

11:00–12:30 ET – Breakout #3
- BL structure and shallow cloud microphysics
- Short-term measurements

12:30–12:45 ET – Short break
12:45–2:15 ET – Breakout #4
- Convection and cirrus
- High-volume data reduction

2:15–2:45 ET – Long break
2:45–5:00 ET – Closing Plenary #3
- Breakout summaries (10 min each = 40 min)
- Challenges (Ann, 60 min)
  - Engaging community
  - Establishing living documents/web pages
- Path forward including plans for PI meeting and website (Jim, 20 min)

Appendix D

Breakout Session Reports

D.1 Breakout 1a: Mixed-Phase and Ice Processes

Breakout Attendees: Matt Kumjian, Ann Fridlind, Gijs de Boer, Greg McFarquhar, Rob Newsom, Cory Ireland, Jim Mather

Summary Authors: Matt Kumjian

Main Discussion re Recommendation Content

Discussion focused on the material in the CPMSG ice processes matrix, including the motivating science question, problems and roadblocks, impact, and research (i.e., retrievals, measurements, models, maturity and readiness of research elements, potential solutions and recommendations, and a roadmap to modeling applications).

The main motivating science question for this topic was purposely broad:

How do ice microphysical processes and their interactions with radiation and dynamics determine the structure, evolution, life cycle, and precipitation of cold clouds?

Ice microphysical processes and cold clouds are critically important for Earth's radiative budget, playing a large role in governing the life cycles and macroscopic structure (and thus radiative properties) of many cloud systems across the globe. Unfortunately, our understanding of these processes is relatively crude, resulting in significant uncertainties in the treatment of ice processes in models at all scales. Improving our understanding of these important processes and their interactions with cloud radiative properties and dynamics will thus improve the representation of these clouds and cloud behaviors in Earth system models.

Main Discussion Regarding Implementation Strategy and Outcomes

Discussion noted that ice processes and mixed-phase processes are too interconnected to artificially separate, and that it would be fine for multiple working groups to share activities (with perhaps one working group chair to lead efforts).

To assess priority/maturity of goals, it was suggested to consider a "readiness level"-type approach similar to NOAA, though with fewer categories. Perhaps "High/Middle/Low" would work well for ARM/ASR. Identifying science that could be considered "low-hanging fruit" for progress in the near term would be desirable. There are two sides of this: the programmatic timeline (ARM) and the scientific readiness (ASR). It is suggested to annotate the matrix for both.

We have a large amount of cloud observations. Is it possible to point to what is done well and what is not? There should be emphasis on being more quantitative in assessment of data quality and accuracy. There was discussion of the importance of a calibration facility (e.g., for in situ measurements), especially for using different probes, etc. Co-location has also been an issue, particularly in situ and radar measurements. This has hindered scientific progress for measurements. We need to think about how to go after this, especially at small scales (on the order of meters) within cold clouds.

It would be helpful to include a column in the matrix for a “roadmap to modeling goals” for each element, with input from both modeling and observational communities to identify specific needs, uncertainties, and other issues. In particular, modelers can provide the level of specificity needed in terms of retrieved parameters or processes, and the tolerable uncertainty. There was interest in identifying statistical relationships between measurements or physical quantities as specific research elements.

Overall, the goal would be to both explain the readiness or maturity/timeline of the science as well as identifying the modeling problem we are trying to solve.

D.2 Breakout 1b: Regime Classification

Breakout Attendees: Scott Giangrande, Yunyan Zhang, Nicki Hickmon, Alyssa Sockol, Adam Varble, Paytsar Muradyan, Mike Jensen, Scott Collis, Rob Wood

Notetaker: Jennifer Comstock

Main Discussion re Recommendation Content

Why Is This Important?

Following the path of recent ARM/ASR ‘data epochs’ and ‘virtual IOP’ activities, initial CPMSG discussions emphasized the potential benefit for ARM to develop methods that inform on ‘regimes’. The term ‘regime’ was kept relatively inclusive in these discussions, covering several concepts for improved data characterization, physical-process identification and/or classification. The motivation for these efforts was, however, to target ‘regime’ breakdowns that encourage the more frequent use/download of ARM datastreams, wherein low use/download has often been attributed to ARM user difficulty in discovering key cloud events or identifying the most useful/calibrated ARM data sets. Specific examples for regime activities as noted by initial CPMSG documentation include: (i) potential ARM changes that recommend optimal data quality/operational windows (possibly, related to ‘Recommended Datastream’ initiative), (ii) products or metadata improvements that identify particular clouds/events of interest, or (iii) practical/functional guidance to determine ideal conditions for running select VAPs/products. Additional consideration was also given to the more traditional PI-science-generated ‘regime’-based approach to identify more digestible data set control groupings (i.e., machine learning synoptic-scale ‘control’ studies, or similar clustering with long-track instrumentation, radiosondes). However, the applicability for these PI ‘research’ methods within ARM has just started to advance (and, highly site specific), so it was encouraged that PIs provide the results of such regimes/clusters as PI products to assess the future demand for such concepts. Finally, higher-end ARM observation/model concepts such as LASSO,

LASSO-O Data Bundles, and visualization therein were noted as a potential ‘best-case’ example that focus PI efforts or containerize ideal ARM data set/metrics/codes. However, CPMSG members raised concern that ramping up or doubling-down on such concepts may be premature, as they have not proven successful/cost-effective.

Fitting ‘regime’ concepts that strive to distill larger problems to core elements, an overarching bottleneck within this CPMSG breakout discussion was the apparent infinite number of possibilities or criteria of interest to the ARM community (e.g., cloud type, synoptic control, data quality, multi-instrument capability). Therefore, a strong recommendation when engaging in future ‘regime’ activities was to begin with clear, simple drivers from the science/infrastructure community (for example, User Executive Committee [UEC], working group chair recommendations, etc.) to be most effective.

Are There ARM/ASR Programmatic Integration Factors?

During this breakout session, there were several points of disconnect between the science and infrastructure representatives. One key discrepancy was in the terminology and interpretation of ARM data quality and associated reporting in ARM (e.g., ‘what would constitute a good quality data set?’). For example, comments centered on current data set quality reports or levels (e.g., data quality reporting, or what is meant by ‘a1’- to ‘b1’-level files), and how these reports or levels often indicate criteria such as ‘up-time’ status, or only the ‘best’ estimate of calibration for the collection time

Two additional longer-term actionable items were identified as outcomes of the session. These efforts are both anticipated to take > 6 months to implement, as these ideas would be contingent on the tasked ARM individuals and/or funding/availability:

1. Provide a simple (e.g., ARSCL-based, satellite, radar) cloud outcome/summary product. This may or may not take the additional step to incorporate this 'class' of cloud-type or similar outcomes into larger metadata/accessible resources.

   This action item was suggested as an activity that the ARM translators/developers may support, e.g., by adapting existing ARSCL-based 'cloud type' classifications, and potentially bolstering these ideas with additional sensor information (e.g., summary statistics from precipitation radar, other sounding parameters, or CPMSG-recommended details).

2. Provide a standardized way to record information during future AMF campaigns; This may be accomplished by the PIs or PIs supported by ARM. These reports would be made available for all ARM users after the campaign, along with standard 'close-out' documents, in a more machine-readable fashion.

   As with the first action item, this activity was suggested as one that may be assigned to an ARM translator, more closely working with the AMF PI, at the start of future ARM AMF campaigns. Translators may provide the necessary guidance to help develop a new ARM system (i.e., web-based form, or similar) in coordination with ARM and the associated AMF campaign PI. These activities may be easier to initially roll out for future AMF campaigns (e.g., Tracking Aerosol Convection Interactions Experiment [TRACER]) that have daily/forecasting type components and summary telecons.

Main Discussion Regarding Implementation Strategy

Overall, there was consensus that "regime" concepts are interwoven into many of the other CPMSG breakout sessions and barriers therein, Nevertheless, there was less consensus whether any particular 'regime' activity should be prioritized to a specific working group or focus area. The identified 'actionable' items are predominantly those that can be handled by existing ARM groups (e.g., translators). Less emphasis was placed on longer-scale concepts such as 'data epochs' or 'virtual IOPs' that are undeniably more challenging to start. One option was to again rely on existing ARM groups (e.g., translators) to start the ball rolling by presenting a strawman recommendation for a particular concept to be iterated on by CPMSG and other stakeholder groups.

Key Findings

"Regime" concepts cross-cut several important CPMSG concepts, but 'regimes' as a bottleneck or barrier may be too broad to tackle disconnected from other breakout sub-sections.

Decisions

Initially, apply simple efforts for improved AMF documentation and further 'cloud type' regime VAPs to inform new metadata tags.

Issues

“Regimes” are difficult owing to the nearly unlimited possibilities. Few ‘one-size-fits-all’ solutions are applicable for all ARM users. However, basic ‘cloud type’ or similar column classifications may be valuable.

Needs

Initially, efforts may be spearheaded by ARM translators as part of their typical efforts.

Action Items

Several simple action items were identified, as outlined above, to be initially reviewed by ARM translators.

D.3 Breakout 2a: Capabilities Review

Breakout Attendees: Jennifer Comstock, Jim Mather, Adam Varble, Paytsar Murydan, Scott Giangrande, Rob Wood, Yunyan Zhang, Cory Ireland, Greg McFarquhar

Notetaker: Jim Mather

Main Discussion Regarding Recommendation Content

ARM deploys ~100 unique instruments and maintains ~70 VAPs each year. Maintaining these capabilities requires resources. In order to stay current and be able to explore new capabilities, ARM must retire outdated or resource intensive instruments or datastreams. ARM has developed a process for reviewing and retiring capabilities that includes evaluating criteria such as scientific impact through publications, data usage, instrument uptime, yearly cost, and uniqueness. ARM plans to review a set of capabilities each year including instruments, data products, and software tools. This breakout session described the proposed process and aimed to gather feedback from the user community. A short list of capabilities that will be reviewed was also presented along with basic user statistics for these capabilities. There was discussion around that list and what the statistics really tell you about a capability.

Main Discussion Regarding Implementation Strategy

The participants asked questions about who will be on the review committee, which was primarily composed of ARM infrastructure staff, and suggested that users should also provide input. As a result, there will be a comment period for users to supply feedback after the committee makes their recommendation.

The remaining discussion was around the short list of capabilities that will be reviewed in the near term. It was suggested that capabilities be examined in terms of their applicability at a given location. For example, scanning cloud radars in their current configuration may not provide scientific value at a site focused on shallow clouds (i.e., SGP), but do provide value at sites studying ice crystal properties or phase (i.e., mixed-phase cloud regimes). This type of information will be considered in the analysis.

D.4 Breakout 2b: Joint Exercises

Breakout Attendees: Ann Fridlind, Corydon Ireland, Mike Jensen, Rob Newsom, Shaocheng Xie, Yunyan Zhang

Summary Authors: Ann Fridlind

Main Discussion Regarding Recommendation Content

Past model intercomparison studies have historically engaged large (sometimes very large) groups of scientists around ARM data sets. Examples include four mixed-phase shallow cloud model intercomparison studies based on the Mixed-Phase Arctic Cloud Experiment (M-PACE), Surface Heat Budget of the Arctic Ocean (SHEBA), and Indirect and Semi-Direct Aerosol Campaign (ISDAC) data sets. Seventeen models internationally participated in the Klein et al. (2009) study, for instance. Most observation-based convective and frontal clouds and cirrus model intercomparisons have also been based on ARM SGP observations.

However, programmatic changes are in part responsible for a decline in such work. The World Meteorological Organization (WMO) Global Energy and Water Exchanges (GEWEX) Cloud System Study (GCSS) program, which operated powerfully as a clearinghouse and mentorship program for case study incubation and participation for many years, has been replaced by the GEWEX Atmospheric System Studies (GASS) program, which has a broader focus that perhaps somewhat diluted the GCSS momentum based on such case studies. On the positive side, GASS has included the Continuous Intercomparison of Radiation Codes (CIRC) project, which can be viewed as a precursor to the Radiative Forcing Model Intercomparison Project (RFMIP).

Over a similar period, some new trends have emerged in ARM data use approaches in the community. For turbulent-layer clouds, a quasi-Lagrangian reference frame has become more common (e.g., Neggers et al. 2019, Silber et al. 2019). There is an increase in the use of nudged or short-term hindcast approaches for climate models in comparison with fixed-site measurements rather than use of the single-column-model approach (e.g., Phillips et al. 2004, Williams et al. 2013, Lubin et al. 2020). The forward simulation approach is also increasingly a leading tool (e.g., Lamer et al. 2018).

This breakout considered the general question of whether it is actionable and desirable to increase efforts to seek and support frameworks that bring individuals and groups together for limited joint exercises. Could these be led from the perspective of producing and using unique integrated data sets? In that case, could there be limited programmatic support to stimulate community code development for “best estimate+” data sets to which PIs might contribute new products or analyses (e.g., clear-sky PBL structure)? Alternatively, could this be led from the climate modeling community within ARM/ASR or other groups? In that case, would it make sense to request that community to identify “hot topics” and see where ARM data set mining could make a unique contributions? An example of this may be the current GASS project on diurnal cycle of precipitation over land led by Shaocheng Xie, which is heavily based on ARM field campaigns for its case studies. How could any such efforts be stimulated?

Key Findings

Regarding the general concept, we agreed that it is a good idea to recommend stimulating joint exercises. Modelers felt that "something was lost" when the Cloud Modeling Working Group ceased to meet as a dedicated group. It was noted that the former Clouds with Low Optical (Water) Depths Working Group (CLOWD) and Quantifying Uncertainty in Cloud Retrievals (QUICR) focus group had successfully provided strong foci for vigorous joint work. On the observational side, it was noted that the Combined HSRL and Raman lidar Measurement Study (CHARMS) provided a similar example for unique instrument pairing, representing a parallel (non-modeling) type of participatory activity that would also benefit from direct stimulation.

Main Discussion Regarding Implementation Strategy

Annual PI meetings present a natural opportunity to initiate and shepherd joint activities via dedicated breakouts. It was suggested that recently completed IOPs with unique instruments could serve as a nucleus for such activities, as could unique data sets at long-term sites (e.g., sub-cloud and in-cloud drizzle at ENA). It was also suggested that climate modelers could meet and consider opportunities related to climate model biases, seeking exercises that relate persistent biases with advancing process-level understanding, similar to the Cloud Above the United States and Errors at the Surface (CAUSES) project. Potential was noted to participate with workshops and meetings, such as ParaCon or Pan-GASS. It was noted that a leading barrier is finding someone to lead group exercises. On the other hand, leadership by younger scientists is promoted by a mentorship tradition within the facility, and there is a benefit to young scientists of working with an expanded group on a project of wide interest (stimulates ideas). It was also suggested that exercises could be smaller in scope and in the past have benefited from duplicating aspects of output reporting (economy of scale over multiple studies).

It was agreed that there is a strong basis for ARM to provide a leadership role in modeling activities internationally, owing to its production of observations and forcing data sets, infrastructure for accommodating activities, and continuity of support from management. It was suggested that a "case library" could be an objective, for instance. There could be a role for DOE laboratories to play, via their more consistent Science Focus Area (SFA)/infrastructure funding support. CAUSES and follow-on work provides an excellent example of that.

Needs

Stimulation of group activities should be driven from the modeling side, but also from the point of specific scientific foci, and observational objectives.

Action Items

We propose to revive some activities driven from the modeling side, ideally focused on specific "hot topic" areas of climate model development. PI meetings are a natural place for that to happen (actionable in 3-6 months). International engagement requires additional vision for development, and parallel activities on the observational side could potentially be supported by openings for short-term measurement deployments (actionable; slightly longer term).

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D.5 Breakout 2c: Open-Source and Community Code

Breakout Attendees: Adam Theisen, Scott Collis, Nicki Hickmon, Aaron Kennedy, Alyssa Sockol, Eric Bruning, Christine Chiu

Notetaker: Nicki Hickmon

Main Discussion Regarding Recommendation Content

Note, due to a limited number of science participants from the CPMSG, external PIs were invited to attend. Aaron Kennedy and Eric Bruning are not members of the CPMSG but did provide very useful feedback.

Why Is This Important?

Funding institutions, ASR included, and journals are moving towards requiring code be posted in an open-source manner as part of their processes. ARM is setting up a process to serve the community and their open-source needs, including the hosting of code under overarching Github organizations.

Are There ARM/ASR Programmatic Integration Factors?

ASR's latest call had specific language about providing code to ARM. ARM will be working with ASR PIs to host their code in an open and searchable manner. ARM's move towards more open-source software will also allow for broader interactions with the ASR community and create opportunities for mutually beneficial collaborations.

What Is Actionable in the Next 3 Months, 6 Months, 5 Years?

ARM will plan to roll out the new processes as they relate to open source by the 2020 PI meeting. Py-ART, ACT, and ADI are currently open source with Py-ART and ACT developed specifically for community use and hopefully in return community contributions. These contributions could in the long run be easily pulled back into ARM processes.

Main Discussion Regarding Implementation Strategy

Open-source software is not only valuable for science but invaluable for undergraduate and graduate education. ARM working to provide open-source software will benefit the university systems and in turn help to train the future workforce that has familiarity with ARM data. It would be useful to have a summer school focused on open source and also additional virtual workshops and tutorials a couple of times throughout the year to educate ARM infrastructure and data users on open-source practices and processes.

A couple of barriers to wider adoption of open-source software and practices were noted. First, while basic coding knowledge is not an issue (python versus c versus idl), properly coding for open-source use is a challenge. Second, there is a social aspect in which users are unsure if they should be contributing code back, especially to larger, well-known repositories. Third, science users tend to focus on working towards theses or papers, so they have no additional motivation for the extra effort to make it open source.

The answer to all of these comes back to education. The first and second barriers could be remedied through tutorials and virtual workshops. The third barrier can be broken down by communicating that open-source software cannot only advance their science but also their career as repositories can have a DOI and are citable. There is a need to ensure that contributors get appropriate credit for submitting their code to these community tools.

An additional request was for the open-source software topic to cover different ways to process large data sets. It was noted that some users just want simple plots or statistics from a large volume of data, but they would currently have to download all the data to get that information. It was noted that the ARM Data Center (ADC) is developing a Jupyter hub that could provide a user access to process data on the ADC systems and then download just the statistics. Also, Cassandra has been used to load up entire data sets and quickly produce statistics.

Key Findings

Key finds and recommendations:

1. Attendees from the science community were very supportive of ARM’s efforts to move towards open-source software.
2. Efforts towards education (science users and ARM infrastructure) would be extremely beneficial. This would include tutorial sessions at the PI meeting, but also workshops multiple times a year and a summer school to educate on the basics and remove any barriers to contributing code.
3. In addition to open-source software, there are other needs for advancing software technologies to help users get at the information they need without having to download entire data sets.

Decisions

NA

Issues

1. Basic coding knowledge is not an issue (python versus c versus idl), but properly coding for open-source use is a challenge.
2. Users are not sure if they should be contributing code back, especially to larger, well-known repositories.
3. Science users tend to focus on working towards theses or papers, so they have no additional motivation for the extra effort to make it open source.

Needs

Resources for the development of education and outreach material as it pertains to open-source coding. This would support PI meeting tutorials, virtual workshops, summer school, and potentially even online courses.

Action Items

We need to reach out to the working group chairs and others in the community (UEC) to get input on what ARM data products or other tools would be most beneficial to consider for development into open-source and/or community code.

D.6 Breakout 3a: Boundary-Layer Structure and Shallow-Cloud Microphysics

Breakout Attendees: Christine Chiu, Gijs de Boer, Ann Fridlind, Cory Ireland, Mike Jensen, Jim Mather, Greg McFarquhar, Paytsar Muradyan, Rob Newsom, Rob Wood, Shaocheng Xie, Yunyan Zhang

Notetaker: Jim Mather

Summary Author: Christine Chiu

Main Discussion Regarding Recommendation Content

This breakout session focused on discussing the issues to be resolved and plans required for advancing science in boundary-layer structures and shallow cloud microphysics. Boundary-layer clouds are one of the main sources of uncertainty in climate change predictions. Improved representations of their properties and processes are necessary for reducing the uncertainty and for predicting how clouds respond to aerosol perturbation and warmer climate.

ARM is particularly well equipped to address the following science questions:

- What processes determine the boundary-layer structure and its interactions with cloud dynamics, microphysics, and underlying surface?

- What processes and interactions determine the precipitation formation, rate, frequency, structure, and evolution of low-topped warm clouds?
- How do these interactions influence cloud dynamics, cloud microphysical and optical properties, and their response to climate change?

The discussions were mainly centered on the designed matrix that details the roadblocks, the status and recommendation of research elements, their impacts, and a roadmap to modeling goals. While the breakout session started out with two separate topics (boundary-layer structure and shallow-cloud microphysics), we soon recognized that they should be considered as whole. This leads to additional roadblocks such as measurements of vertical velocity (from boundary layer, cloud base to in-cloud); observations of small-scale turbulence, entrainment, and mixing; and capability of observing clouds in precipitating conditions. The attendees provided expertise in ground/aircraft instrumentation, retrieval, data analysis and modeling, nicely covering many aspects of the matrix.

Main Discussion Regarding Implementation Strategy

This section summarizes 1) the main discussions, 2) the reason for the level of readiness and preparedness assigned, and 3) recommendations for each roadblock. These roadblocks are grouped by measurements of cloud, aerosol, dynamic/thermodynamic, and surface, and the level of readiness/preparedness is indicated in ( ) in the subtitle.

Cloud

Robust observations for clouds with low liquid water path (LWP) (   )

ARM has techniques using the atmospheric emitted radiance interferometer (AERI) measurements that can provide retrievals for clouds with up to LWP of 60 g m^{-2}. The level of readiness/preparedness is high, because the technique is mature, though expensive to run. It appears that the retrieval product has been provided for certain sites, time periods, or projects like LASSO, but not more broadly. A possible pathway to move forward is that the working groups prioritize the needs and work closely with translators to process the retrieval. We also need to think about what we can do now that could extend the Routine ARM Aerial Facility CLOWD Optical Radiative Observations (RACORO) campaign in 2009 over the Southern Great Plains (SGP). Note that the difficulty in measuring small clouds occurs in aircraft platforms as well, which we should keep in mind and start to address.

Robust observations for clouds with high liquid water path (   )

The need for the capability of measuring LWP in raining conditions has been stressed for a long time. Solutions could include 1) to enhance the capability of MWR so that it can operate in raining conditions; and 2) to develop retrieval methods using dual-frequency radar measurements). Since these ideas are not new and have been developed to a certain degree, the readiness/preparedness is assigned as the mid-level. The integration of ARM/ASR may be needed to push this forward.

Robust observations for detailed cloud microphysical properties, including cloud droplet number concentration and joint cloud/drizzle retrievals (   )

This roadblock was discussed extensively, partly because of its scientific importance and high demands from the modeling community, and partly because of the ARM's unique leading role in this particular field. Two key recommendations emerged from the discussions. First, several retrieval methods exist in the ARM/ASR community, ranging from the mature VAP Droplet Number Concentration (NDROP) that is based on an adiabatic assumption to more sophisticated algorithms that relax the assumption but have not been extensively evaluated. To move forward, solutions could be to ensure that NDROP is processed for sites like ENA and NSA, and to facilitate joint activities for evaluating detailed cloud microphysical properties. Second, measuring cloud drop number concentration, or in general, cloud properties, is never easy even for in situ observations. A more integrated view of bridging in situ, remote sensing, the tethered balloon system (TBS), and unmanned aerial systems (UAS) can help to address scale and evaluation issues and to provide more routine observations, especially for warm clouds. This, of course, heavily relies on good instrument calibrations in all platforms.

Aerosol

Quality and availability of aerosol measurements

We have not been able to discuss this roadblock extensively, mainly because we did not know well enough about the outcome and recommendations from the Aerosol Working Group. However, we stress the importance of knowing what is happening at cloud level, not only about cloud condensation nuclei but also ice nucleating particles. We also second the ongoing efforts and plans that improve characterizations of aerosol profiles, using combined observations from remote sensing and in-situ via TBS and UAS.

Dynamics sand thermodynamics

Difficulty in characterizing boundary-layer height and structure ( )

This roadblock concerns three issues. First, the comprehensive lidar and radar instrumentations of ARM can provide several key observables to address this roadblock, but the level of readiness/preparedness varies. For temperature, continuous measurements from Raman lidar are VAPs, but temperature fluxes are not available because temperature measurements remain noisy. For moisture, fluxes can be derived from Doppler lidar (DL) and Raman lidar (RL) measurements, but the technique is not operational. For variance of vertical wind speed, products are available from DL and the radar wind profiler (RWP). However, it can be challenging to apply remote-sensing techniques to high-latitude sites (e.g., very shallow boundary layer). It might be useful to come up with best practices for high-latitude sites, and UAS can provide a function to alleviate the issue.

Second, since planetary boundary-layer (PBL) height is a poorly defined quantity, we recommend focusing on observables like profiles of turbulence that are related to PBL height.

Third, it remains challenging to relate these observables obtained at high temporal and spatial resolution (e.g., retrievals from RL at 60-m resolution) to models, especially given the lower resolution of the models. This challenge highlights the struggle of moving this area forward. Since part of this challenge is the focus of the lidar breakout session in the upcoming PI meeting, we recommend soliciting input from that session and perhaps forming a small group to construct a more specific plan.

3D spatial context of boundary layer ( )

The Land-Atmosphere Feedback Experiment (LAFE) provides a model for how to obtain 3D boundary-layer structure, using a combination of vertically staring and scanning DL. In addition to lidar, there are also radar techniques that ARM has not done much with. Approaches with less expensive distributed measurements, e.g., getting 2D information, are also possible. While observations from these techniques may not be appropriate for addressing the forcing question at large scale, they can be used to study mesoscale variability, cold pools, dry lines, internal jets, etc., or drainage flows observed during RACORO.

Constraining large-scale vertical motion (To be determined)

While forcing data is necessary for modelers to drive models, the context and scientific motivation of this barrier was unclear to the attendees. We recognize that this is a challenging problem, but the constraints can be provided by RWP, DL, drop sounding, surface flux measurements, or buoy data at ENA, etc. Surface fluxes are directly used as the constraints in the ARM variational analysis. The vertical profile of latent heating or in-cloud vertical velocity retrieved from ARM radars can be considered as an additional constraint to be incorporated into the variational analysis to constrain the vertical structure of its derived large-scale vertical motion or independent information for evaluation. Recent activities have also started assimilating the large-scale state (horizontal wind fields, temperature, and moisture) information from RWP and DL to improve forcing data. This barrier has also led to discussions on advective tendencies of hydrometeors, which may be more important but not included in the current large-scale forcing data set. Soliciting input from working groups will help further clarify the context and scientific motivation of this barrier and the needs from the community, as listed in Action Items at the end of the report.

Interactions with surface

Characterizing surface properties and inhomogeneity

The roadblock was initially referred to the issue in boundary-layer analyses at ENA, which requires ocean-surface properties. Since satellite observations can provide sea surface temperature to about a half degree accuracy, it is possible to obtain surface fluxes through model simulations. Though evaluating modeled flux is needed, it has not been considered as the highest priority based on the discussions. Instead, charactering latent and sensible heat fluxes and their spatial variability over land are considered as a higher priority. It is hoped that more work will be done in this area at the southeast site.

Action Items

In the upcoming PI meeting:

- Solicit input from working groups to clarify a few barriers that were unclear to the attendees and thus no specific recommendations were proposed. These barriers include surface inhomogeneity, the need of ocean measurements at ENA, adaption and development of remote-sensing techniques for high-latitude sites, and the need for constraining large-scale vertical motion.
- Solicit input from breakout sessions, e.g., the lidar group for characterizing boundary-layer structure and obtaining 3D structure and spatial context.

D.7 Breakout 3b: Short-Term Measurements

Breakout Attendees: Scott Collis, Nicki Hickmon, Scott Giangrande, Adam Theisen, Jennifer Comstock, Alyssa Sokol, Adam Varble, Andrei Lindenmaier

Notetaker: Adam Theisen

Main Discussion Regarding Recommendation Content

Why Is This Important?
Are There ARM/ASR Programmatic Integration Factors?
What Is Actionable in the Next 3 Months, 6 Months, 5 Years?

The group decided that having flexible short measurement modes was an important new area for ARM to pursue for the more complex instrumentation (lidar, radar) for two reasons: Episodic collection with regular scheduled down time will lead to high-quality measurements when instruments are collecting data and PI-driven sampling modes are more likely to lead to better value outcomes (papers) than “catch all” modes that are ignorant of the temporal and spatial scales of the phenomenon being studied.

However, the group raised two critical caveats: One, these “special modes” should not come at the cost of high-quality, calibrated b-level products; two, PI access to deciding what these operation modes are should be fair and equitable, with no insider access.

The main actionable item is for infrastructure to design a strawman proposal as to how such access would work, likely based around the current AMF/IOP proposal system. Once put in place (after review, etc.), it will be essential to make known that requesting specific operational modes of complex assets is possible. This will be achieved through outreach and highlighting the new procedure (even if it is only an extension of existing procedures) to stakeholders, likely at programmatic meetings and society meetings (American Geophysical Union/American Meteorological Society).

While outside the purview of ARM, it was noted that for special operations modes to be scientifically successful (again, scientific insight as measured by publications), ASR or other science funding would be ideally linked. Therefore we suggest that ASR be aware of these modes.

Finally, if ARM is to adopt this new paradigm for operations of the most complex clouds and precipitation measurements, it is vital to stick to this mode for an appreciable amount of time to truly judge the efficacy and to give the science community time to adjust to the “new normal”.

Main Discussion Regarding Implementation Strategy

ARM has taken on the operation of increasingly complicated instruments to the point that we are always playing catch up and it is hard to get properly calibrated and characterized systems (Why is this an important topic?).

Often, we are scanning “nothing” with these systems, but that “nothing” could be important as well (clear air scans for radar). Doppler lidars are in vertically pointing (VPT) and simple velocity-azimuth display (VAD) modes (initially was higher resolution but was slowly decreased for higher-temporal-resolution wind data in support of LASSO).

Can we have a system where ARM stakeholders can come and be in a constant IOP mode?

The X-Band summer experiment was a key example of configuring a complex instrument to go after a specific science question. Good data were collected but there were two serious issues with the way this was carried out:

1. Decisions were made behind closed doors. There was no opt-in method for the wider stakeholder community. This was not a fair and level playing field.
2. The funding that stakeholders held was not very well aligned with the science goals laid out. The experiment was a quick and agile perturbation to their work and it was difficult to give the new data attention. It would be good to have science effort (outside of ARM's domain) tied to special modes.

It was pointed out that the science supporting the X-Band modes may have been better carried out by the SFA-funded labs as they have a broader remit for doing science and showing value to DOE. The Experiment helps highlight the importance of equitable access.

What's a better mechanism to allow for these short-term activities? More formalized process so that mentors and ARM can plan. Then we could address people getting funding. People ask for the deployment of instruments in ASR and DOE early career proposals.

- Clarity and clear process are vital to ensuring an open process that does not leave people out.
- ARM has a formalized process for field campaigns so anyone can propose anything. It is open to the community and everyone should use it.
- We need to make clear that this is possible. It has never been clear that changing the operational modes of instruments was possible. Communications and outreach are critical.
- AMFs already have some of this built in. PIs request what they would like out of those scanning systems and iterate on the science and operations. Our issue seems to be what to do with the fixed sites.

Point of agreement: When we run in a specialized mode, then the PI that proposed/set up that project really owns it and the data is far more likely to be turned into a publication.

- It is good to have PIs engaged and giving feedback, but ARM also thinks about the wider community. The PI can push for things but cannot control a lot.
- We need to set our expectations and goals for data quality:
  - Less radars, more focus on radar data may help with data quality but we should always be shooting for b1-level data.
  - The fundamental problem is a shortage of resources.

Key Findings

- Special operational modes will benefit science by targeting specific phenomena and helping PIs "own" the science and use ARM data to vigorously attack a science question.
- Access MUST be equitable. Stakeholders must know these modes are possible and know how to apply to ARM to configure complex instruments in their desired mode.
- Having episodic down time will lead to better data when the instruments are up.
- Linking ASR funding to these modes will greatly increase the likelihood the data will get the deserved attention and lead to products and open-source codes that will benefit the community outside of the proposer's group.
- Not all complex instruments should be included. A key exclusion could be the SEUSA site, which has clear science goals as laid out by the SEUSA science team.
- All of this cannot come at the expense of quality controlled, calibrated b-level data.

Decisions

ARM should continue to explore these ideas and return with more solid examples as to how this would work.

Issues

A key issue raised was the complete disconnect between the ARM-funded Cloud, Aerosol, and Complex Terrain Interactions (CACTI) campaign and the ASR funding to support research on retrievals and processes using the data. The disconnect between cycles caused a failure to "strike while the iron is hot".

A second issue was raised, aligned with the comment on quality data, that the radars appear to be an enigma to the Data Quality Office, with difficulty experienced getting answers on data-quality issues identified by staff and student analysts. Clearer communications will be essential if we move into an episodic mode so DQO effort is not wasted.

Action Items

The group supports a new paradigm of operations for complex instruments. ARM should draft procedures on how this could work and circle back.

D.8 Breakout 4a: Convection and Cirrus

Breakout Attendees: Jennifer Comstock, Ann Fridlind, Scott Giangrande, Nikki Hickmon, Cory Ireland, Michael Jensen, Greg McFarquhar, Adam Varble, Rob Wood, Shaocheng Xie, Yunyan Zhang

Summary Authors: Mike Jensen

Main Discussion Regarding Recommendation Content

Our discussion focused on the material in the CPMSG convection matrix including motivating science questions, problems and roadblocks, impact, research elements (i.e., retrievals, measurements, models, maturity and readiness of research elements, potential solutions and recommendations, and a roadmap to modeling applications.

Three main motivating science questions were identified for this topic:

1. How do coupled dynamical and microphysical processes drive convective life cycle, and radiative and precipitation properties?
2. How do convective processes and properties and their relationships with/feedbacks to the environment vary in different regimes?
3. How do ice cloud microphysical processes vary under different environmental conditions?

Deep convective clouds are important drivers of the atmospheric circulation and transport mass, momentum, heat, water, aerosols, and chemical species through the depth of the troposphere while cirrus clouds play an important role in the heating of the upper troposphere. Improving our understanding of the dynamical and microphysical characteristics of both cloud types is an important step towards realistic representation of clouds in Earth system models, and improved simulation of future climate states.

Main Discussion Regarding Implementation Strategy

Several specific roadblocks to progress in gaining new understanding of the coupled dynamical and microphysical processes that drive convective life cycle were identified including: (1) uncertainties in vertical velocity and microphysics retrievals, (2) rapid evolution of convection requires specialized observational approaches, (3) poorly observed localized, four-dimensional environment has significant impacts on dynamics and microphysics and (4) need for more detailed observations of convection in varying environments.

In addition, roadblocks to our improved understanding of cirrus cloud processes were identified including: (1) need for high-quality retrievals of ice microphysical properties, (2) humidity measurements near and within clouds, (3) improved mass-dimensional relationships, (4) measurements or retrievals of vertical wind speed variance, including gravity waves.

For each of these roadblocks, several potential solutions were discussed among which common recurring themes were: (1) The need for calibrated and well-characterized remote-sensing observations, particularly from the ARM radar systems, (2) the need for additional in situ aircraft observations, and (3) the need for more detailed observations of the environment (thermodynamics, kinematics, and aerosol) in which the convection and cirrus form and go through their life cycle. In some cases, the technology, measurements, and algorithms are available to make progress towards specific solutions, and in some cases further development is needed.

Key Findings

The ARM facility makes many of the necessary measurements for addressing important gaps in our understanding of convective and cirrus cloud processes; however, some problems and roadblocks impede progress. The highest priority is a focus on obtaining high-quality, calibrated radar data sets in a variety of environments. These remote-sensing measurements need to be combined with in situ aircraft measurements during short-term campaigns that serve to validate retrieval algorithms, providing information on sub-measurement scale properties leading to an ability to put long-term measurements in proper context. In addition, characterization of the local environment, including the thermodynamic, kinematic, and aerosol characteristics, is needed. Advances in these areas can be made with additional analysis and product development from existing measurements, but some progress will require new investments in instrumentation, retrieval development, and modeling activities (see CPMSG convection matrix for details).

Decisions

The development of the CPMSG convection matrix is meant to provide a framework for identifying science-driven needs for advancement of our understanding of convection and cirrus cloud properties and processes and proposing potential solutions with requisite information on the technical readiness of the solution components. This matrix is meant to be a living document providing an avenue for additional input from the research community. The identified problems and roadblocks, and accompanying proposed solutions, are meant to provide guidance to the ARM facility in making decisions on priorities and investments that will have the greatest impact on scientific advancement.

Issues

For convective studies in particular, a variety of different measurement approaches are needed. Both short-term targeted campaigns, with specialized instrumentation (including in situ aircraft observations), and long-term measurements aimed at developing climatologically relevant relationships are needed. During these campaigns, different measurement strategies must be considered, for example, regarding scanning radar observations, slower scans are required for accurate microphysical retrievals while rapid scans are needed to capture kinematic variability.

Needs

Some of the potential solutions are achievable with current ARM instrumentation and resources such as focusing on fewer radars to provide high-quality, calibrated measurements, or development of VAPs. In some cases, additional field campaign measurements (including aircraft) are necessary and are within the scope of current ARM capabilities, but will need more lead time. In some cases, interagency partnerships, significant new investments, or even new technological advancements are needed such as phased-array radar, storm-penetrating aircraft, or near- and in-cloud humidity measurements.

Potential Action Items

- Prioritize radar systems and focus on fewer radar systems with calibrated, corrected data.
- Addition of targeted radiosonde launches (e.g., afternoon at SGP).
- Apply retrieval techniques (e.g., Kalesse et al.) to additional data sets.

- Provide a brief summary of potential issues with existing retrieval techniques and raw radar data (e.g., calibration issues) for facilitating better use of retrieved radar products and guiding future improvements.

- Plan to provide calibrated data from ARM remote-sensing instrumentation.
- Prioritize VAPs and follow-on analysis of existing cloud microphysical property and vertical velocity retrieval algorithms.
- Explore data assimilation or machine learning approaches, through LASSO, for vertical velocity estimation.
- Development of automated cell-tracking algorithms for scanning radar.
- Testing, development, and validation of CCNPROF VAP.

- Collection of additional in situ data sets (aircraft or balloon platforms may be options).
- Hosting of guest phased-array radar systems, with consideration of future instrument investments.
- Distributed thermodynamic- and wind-profiling networks.
- Deployment in additional convective regimes, particularly tropical oceanic, also including revisiting locations with latest instrumentation.
- Need for confidence flags and uncertainty estimates on long-term retrieval data sets.
- Investment in instrument development for near- and in-cloud measurements of humidity.

References

Kalesse, H, T Vogl, C Paduraru, and E Luke. 2019. “Development and validation of a supervised machine learning radar Doppler spectra peak-finding algorithm.” *Atmospheric Measurement Techniques* 12(8): 4591 4617, https://doi.org/10.5194/amt-12-4591-2019

D.9 Breakout 4b: High-Volume Data Reduction

Breakout Attendees: Rob Newsom, Adam Theisen, Alyssa Sockol, Christine Chiu, Matthew Kumijan, Paytsar Muradyan, Scott Collis.

Notetakers: Jim Mather and Rob Newsom

Main Discussion Regarding Recommendation Content

Why Is This Important?

The issue is that Doppler spectra (either radar or lidar) potentially contain a wealth of information relevant to cloud and precipitation research, but because of the sheer size of these data sets and the small user base, the information content has not been fully explored. This is particularly the case for the lidar spectra.

Although we know that the lidar spectra are useful for precipitation studies (e.g., they enable direct measurement of the terminal fall speeds), there are still a lot of things we do not know about the lidar spectra. This includes their behavior at or near cloud base or inside optically thin clouds. We do not yet know how useful the lidar spectra might be in the study of turbulence in the atmospheric boundary layer. One question is: What is the relationship between spectral broadening and total kinetic energy (TKE) or dissipation rate? Can the spectra be used to retrieve TKE and/or dissipation rate? There are many interesting topics to explore here.

The size of the spectral data set presents logistical challenges for infrastructure in terms of bandwidth and storage. On the science side, use of these data sets is limited to a relatively small group of individuals with experience in radar and/or lidar signal processing.

So I see a couple of problems here. The first is related to the technical and logistical challenges associated with large data sets like the lidar spectra. This can be handled through the application of compression techniques, and by limiting data collection to only specific periods of interest (i.e., when certain meteorological conditions exist). The second problem is more a of public relations issue. In order to fully explore the information content of the retrieval, it would be helpful to have more people working on it. So more people need to be made aware.

In the case of lidar, the estimate for the raw data volume is roughly 90 Gb/day for the Stream Line XR system (at SGP C1) and roughly half that data rate for the other models. These estimates include the size of the original vendor-generated files (roughly 60Gb/day) plus the output from our current ingest (roughly 30Gb/day). We note that the current ingest already results in a considerable reduction in the size of the raw spectral data when compared to the original vendor files. Most of that reduction is simply the result of converting the 8-byte word structure in the vendor files (i.e., double precision) to 4-byte words (i.e., single precision). Several additional steps could be incorporated into the ingest that would further reduce the file size without loss of information, e.g., conversion from float to short and use of floating point scale and offset parameters.

The data volume estimates above assume that ARM throws nothing away (once collected). If, on the other hand, the raw vendor files were discarded after ingest processing, we would just have to deal with the output from the ingest, which is roughly 30 Gb/day for the XR system using the current ingest.

Another thing that could be done in the very near term is to modify the ingest so that only the first 3 or so kilometers of range are retained in the output. Currently, samples are saved at 3-m intervals from 0 to about 10km. The lidar's range can vary from 0 to maybe 5km or so on a good day. The typical range is about 2 to 3 km. So most of the higher signal-to-noise ratio (SNR) data would be retained by simply truncating the data set at 3km. With this change the data volume would go from roughly 90Gb/day to about 70Gb/day if the raw vendor files are saved. If the vendor files are not saved, the data volume would be only 10Gb/day.

As suggested by Scott Collis and others during the breakout, one solution might be to locate an edge computing system on site to handle processing of the spectral data locally. Such a system could be set up to ingest the raw vendor files and produce compressed spectral output. Additionally, the edge computing system could be used to reprocess the velocity, SNR, and attenuated backscatter data using improved algorithms. There are known issues in the real-time output (i.e., the current standard data product) that could be corrected by reprocessing the raw data on a dedicated server with sufficient horsepower.

For data reduction, algorithms can be implemented on the edge computing system that identify when certain meteorological conditions exist. The system could then save spectra recorded only during periods of interest. Since this would likely require significant development, I see this as a long-term solution.

Are There ARM/ASR Programmatic Integration Factors?

To increase awareness of the lidar spectral data set, it was suggested that we consider forming a focus group centered on the science that can be gleaned from lidar/radar spectra. This focus group could organize and execute joint exercises focused on cooperative measurements between the lidar/radar and other sensors. These efforts might require some programmatic integration.

What Is Actionable in the Next 3 Months, 6 Months, 5 Years?

In the near term (less than one year), the following steps could reasonably be taken:

- Collect additional lidar spectral data during selected periods:
  - Variety of meteorological conditions
  - ENA and SGP.
- Modify ingest:
  - Reduce maximum range of output
  - Represent floating-point data using 2-bytes integers with floating-point scale and offset parameters
  - Other simple compression methods.
- Perform joint exercises focused on cooperative measurements between the lidar/radar and other sensors.
- Form focus group geared towards science applications of Doppler spectra?
- Develop and test code to run on edge computing system.

For the longer term (less than five years out) a goal could be to develop, test, and deploy an edge computing system at SGP or other sites. This system would handle the ingest and processing of the lidar spectra and would decide when to save or toss spectra based on knowledge of the current meteorological conditions.

Main Discussion Regarding Implementation Strategy

Development of an onsite edge computing system will require acquisition of appropriate hardware. It is likely that we would be able to leverage ongoing Laboratory Directed Research and Development (LDRD) work (i.e., Scott Collis's LDRD project). In the near-term, we could do the following using currently available computing resources:

- Adapt/develop and test algorithms for processing the raw lidar autocovariance data.
- Develop algorithms that can determine when certain meteorological conditions exist so that a decision can be made to save or discard data for a particular period.

Appendix E

Workshop Participants

Science User Panel Members

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Christine Chiu	Colorado State University
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Matt Kumjian	Pennsylvania State University

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