Integrating High-Resolution Modeling with Diverse Field Campaign Observations through an Open Science Summer School

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WHAT: To advance atmospheric science workforce development, twenty-three undergraduate, graduate, and early career scientists from around the world came together to learn about ARM data and open-science tools, utilizing observations and simulations to answer scientific questions and test their hypotheses.

WHEN: 19-24 May 2024

WHERE: Cleveland State University, Cleveland, Ohio

1. The Summer School

The Atmospheric Radiation Measurement (ARM) user facility (Mather and Voyles 2013) is a U.S. Department of Energy user facility that collects diverse earth system measurements aimed at improving the representation of radiatively important processes in models across scales. High-resolution modeling efforts, specifically the Large Eddy Simulation ARM Symbiotic Simulation and Observation (LASSO, Gustafson et al. 2020) activity, complement and contextualize these observations by generating petabytes of simulations of the evolving atmospheric and surface structure around ARM observations. LASSO simulations currently focus on the ARM Southern Great Plains (SGP) atmospheric observatory and Sierras de Córdoba region of Argentina, which was the location of the mobile ARM facility during the Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign (Varble et al. 2021). ARM's workforce development efforts include hosting a summer school to foster a rising class of atmospheric scientists to use the existing suite of ARM observations to advance scientific understanding of the Earth system and create a runway for them to ideate on how ARM observations can, in the future, further advance and inform this understanding of the Earth system.

The summer school was sponsored by the ARM user facility, wherein travel support was provided for a majority of the attendees. The summer school student cohort consisted of undergraduate (1), graduate (18), and early career scientists (4) who were selected from a highly competitive pool of candidates, with scientific interest and financial need being the key criteria for invitations to attend (Figure 1). A total of 23 students attended and 12 instructors participated, representing 22 institutions both domestic and abroad (Figure 2).

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Figure 1. A picture of all the participants and instructors in 2024 ARM Summer School at Cleveland State University.

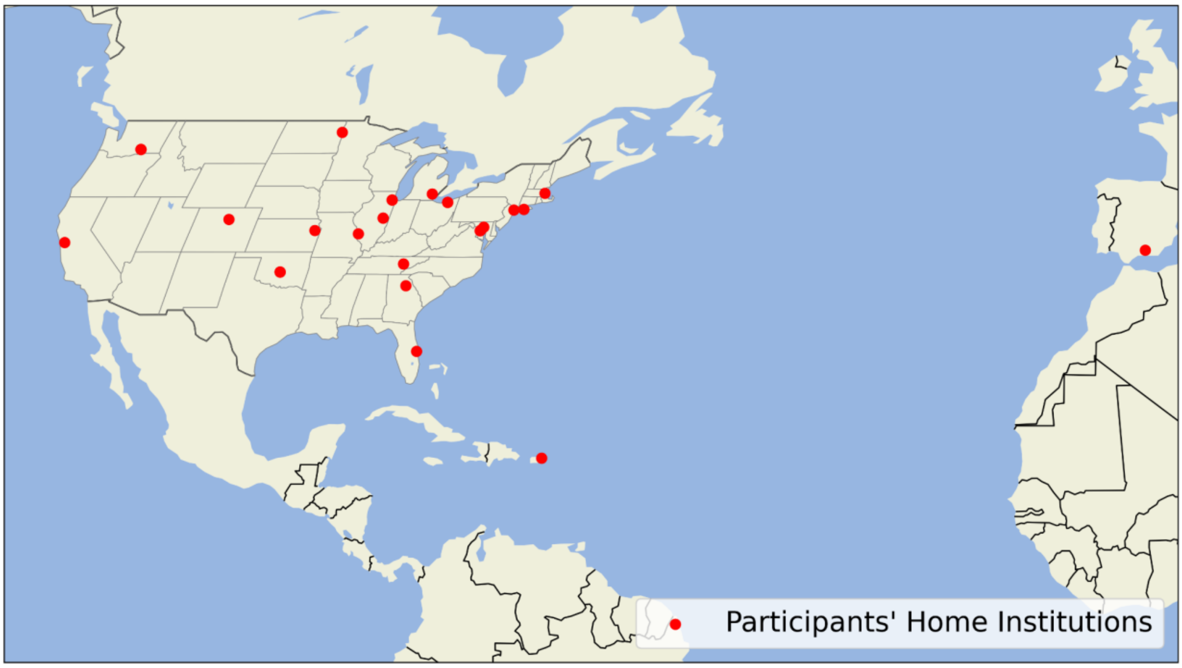

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Figure 2. A map of participants' home institutions, with 1 undergraduate student, 2 masters students, 16 PhD students, 4 early career researchers, and 12 instructors.

While ARM has hosted summer school events in the past (Ghate et al. 2019), this was the first event to focus specifically on open-science and the use of state-of-the-art open source tools to analyze ARM measurements and share results. Instructors shared their expertise as it relates to the core software tools such as the Python ARM Radar Toolkit (Py-ART) (Helmus and Collis 2016) and Atmospheric data Community Toolkit (ACT) (Theisen et al. 2024), atmospheric instrumentation, and core ARM data products. The schedule was designed such that it was a blend of scientific and technical lectures in the mornings, with dedicated group work time in the afternoon wherein students applied the principles from the morning lectures to their scientific projects (Table 1).

Instructors represented a wide range of scientific expertise and covered the full data workflow, including ARM instrument mentors (responsible for ensuring instruments are operational), individuals from the ARM data quality office (DQO) (responsible for ensuring quality assurance and quality control are applied properly), and individuals from the ARM Data Center (ADC) (responsible for ensuring all ARM data is findable, accessible, interoperable, and reproducible). Open-source software to work with the data was extensively utilized. The event served as a venue for instructors to gather feedback from and collaborate with scientific users, and to ensure that the students learn new tools available from the ARM user facility. Instructors served as project mentors, collaborating with the individual teams and offered advice and feedback on students' own research.

Date	Time	Topic	Presenter
Sunday 19 May 2024	6:00 PM - 7:00 PM	Welcome and Icebreaker	Maxwell Grover and Scott Collis
Monday 20 May 2024	08:30 AM - 09:30 AM	Intro to ARM + Welcome	Sally McFarlane and Jim Mather
Monday 20 May 2024	09:30 AM - 10:00 AM	Coffee Break	
Monday 20 May 2024	10:00 AM - 11:00 AM	Intro to ARM Data Workbench	Sujata Goswami and Michael Giansiracusa

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Monday 20 May 2024	11:00 AM - 12:00 PM	Intro to ARM Open Source Software	Scott Collis and Joseph O'Brien
Monday 20 May 2024	12:00 PM - 01:00 PM	Working Lunch: Elevator Pitch Intros	Maxwell Grover
Monday 20 May 2024	01:00 PM - 01:45 PM	Intro to COMBLE-MIP	Timothy Juliano
Monday 20 May 2024	01:45 PM - 02:30 PM	Intro to LASSO	William Gustafson
Monday 20 May 2024	02:30 PM - 03:00 PM	Coffee Break	
Monday 20 May 2024	03:00 PM - 03:45 PM	Intro to SAIL and WRF Model Data	Daniel Feldman
Monday 20 May 2024	03:45 PM - 05:00 PM	Break into Groups! Find data!	Maxwell Grover and Scott Collis
Tuesday 21 May 2024	08:30 AM - 09:30 AM	AI/Machine Learning for Data Quality	Mia Li
Tuesday 21 May 2024	09:30 AM - 10:00 AM	Coffee Break	
Tuesday 21 May 2024	10:00 AM - 11:00 AM	Aerosol + Profiling Measurements in ARM	Damao Zhang and Robert Jackson
Tuesday 21 May 2024	11:00 AM - 12:00 PM	Intro to ARM Radar Data Products	Ya-Chien Feng and Joseph O'Brien
Tuesday 21 May 2024	12:00 PM - 01:00 PM	Working Lunch: Intro to xwrf	Maxwell Grover
Tuesday 21 May 2024	01:00 PM - 05:00 PM	Break into Groups: Plot Data!	
Wednesday 22 May 2024	08:30 AM - 09:30 AM	An Introduction to LES Modeling	Thijs Heus
Wednesday 22 May 2024	09:30 AM - 10:00 AM	Coffee Break	
Wednesday 22 May 2024	10:00 AM - 11:15 AM	Analyzing Data from LASSO at Scale	William Gustafson and Maxwell Grover

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Wednesday 22 May 2024	11:15 AM - 12:00 PM	Instrument Simulators 101 with COMBLE	Robert Jackson
Wednesday 22 May 2024	12:00 PM - 01:00 PM	Working Lunch: Installing Python Locally	Maxwell Grover
Wednesday 22 May 2024	01:00 PM - 05:00 PM	Break into Groups: Ask Questions!	
Thursday 23 May 2024	08:30 AM - 10:00 AM	Radar Data Retrievals	Joseph O'Brien
Thursday 23 May 2024	10:00 AM - 10:30 AM	Coffee Break	
Thursday 23 May 2024	10:30 AM - 12:00 PM	Office Hours: How is it going?	
Thursday 23 May 2024	12:00 PM - 01:00 PM	Working Lunch: Dask 101	Max Grover
Thursday 23 May 2024	01:00 PM - 05:00 PM	Draft Presentations and Demos	
Friday 24 May 2024	08:30 AM - 09:00 AM	Next Steps with the Jupyterhub + ARM	Michael Giansiracusa
Friday 24 May 2024	09:00 AM - 09:30 AM	LES and Climate Modeling with COMBLE	Ann Fridlind
Friday 24 May 2024	09:00 AM - 09:30 AM	Survey Time + Coffee	Maxwell Grover and Scott Collis
Friday 24 May 2024	10:00 AM - 12:00 PM	Project Presentations: Notebooks!	
Friday 24 May 2024	12:00 PM - 01:00 PM	Working Lunch: Contribute to Pythia	Maxwell Grover
	01:00 PM - 01:30 PM	Closing Remarks	Maxwell Grover and Scott Collis

Table 1. Schedule from the 2024 ARM Summer School including date, time, titles and associated links to the presentations as well as the presenter(s).

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2. The Projects

On the afternoon of the first day, students were encouraged to separate into groups and present a project pitch with the following constraints:

- ARM data needs to be used for at least part of the project.
- Scientific questions and associated hypotheses needed to be formed around the available data.
- All materials needed to be developed using Jupyter Notebooks (Granger and Pérez 2021).
- Both observations and simulation data need to be used.

Students gained valuable experience forming testable scientific hypotheses and crafting science questions to address these hypotheses. Following the project pitches and receiving feedback from instructors, students began refining their questions. They then located associated datasets and created Github repositories following the Project Pythia cookbook template (Rose et al. 2023). Throughout the week, students wrote computational workflows that aimed to answer their questions and test their hypotheses, with daily updates at the conclusion of each day. Instructors served as mentors throughout the process, providing feedback on preliminary results and responding to technical difficulties related to cyberinfrastructure or associated open-source tools. The projects are described below, including the members of the group, scientific questions, hypotheses, and ultimate outcome from the project.

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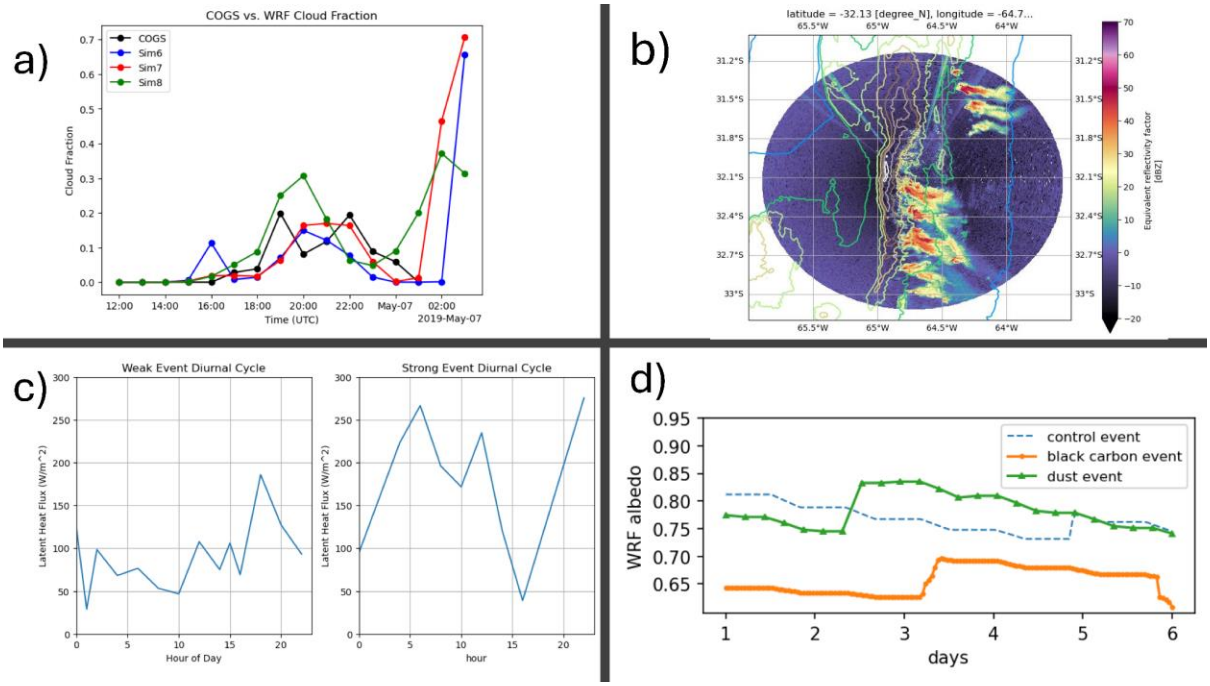

Figure 3. Key figures from each group project: (a) Large Scale Forcing Impact on Shallow Cumulus Fields over SGP, (b) CACTI Deep Convection Initiation, (c) Comparing Cold-Air Outbreak Conditions at COMBLE and the North Slope of Alaska (NSA), (d) Aerosol Influence on Snow Albedo During SAIL.

a. Large Scale Forcing Impact on Shallow Cumulus Fields over SGP

The SGP-oriented group worked with LES simulations over the SGP site, with a specific focus on shallow cumulus clouds and the factors controlling the evolution of these cloud fields in the simulations (Raghunathan et al. 2024).

1) Team Members

- Theresa Lincheck, University of Oklahoma
- Xena Mansoura, Pacific Northwest National Laboratory
- Tessa Rosenberger, Cleveland State University
- Girish Nigamanth Raghunathan, Cleveland State University
- Kyoungho Ryu, Boston University

2) Science Questions

- What does the organization and structure of the shallow cumulus field look like in LASSO simulations on April 4, 2019?

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- How does this organization and structure of shallow cumulus differ from observations on April 4, 2019?
- How does near-surface moisture influence evolution of shallow cumulus?

3) HYPOTHESES

- The scale of large-scale forcing that will yield results closest to observations depends on the date—there is no "one-size-fits-all" scale size.
- Increased surface moisture will cause earlier timing of shallow cumulus creation and deeper clouds (looking at observations on LASSO case dates).

4) OUTCOMES

Varying large-scale forcing scenarios, indicated by Sim 6-8 in Figure 3a, impact cloud core fraction due to differences in turbulent kinetic energy. The model should carefully choose the large-forcing length scale to represent the environment appropriately on a given day.

b. CACTI Deep Convection Initiation

The CACTI group utilized ground-based precipitation and cloud radar data to investigate convection near complex terrain and the associated meteorological forcing mechanisms. They combined LASSO-CACTI simulations (Gustafson et al. 2023) with the observations from ARM's mobile facility and NOAA remote sensing data (Henao-Roldan et al. 2024).

1) TEAM MEMBERS

- Alfonso Ladino, University of Illinois Urbana-Champaign
- Dhwanit Mise, University of Oklahoma
- Victor Ojo, University of North Dakota
- Natalia Roldan, University of Maryland
- Eddie Wolff, University of Illinois Urbana-Champaign

2) SCIENCE QUESTION

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- How is deep convection initiation controlled by local and regional meteorological conditions (thunderstorm life cycle) as well as geography?

3) HYPOTHESIS

- Convection initiation near the ARM site is caused largely by orographic effects, surface heating, and advection of moisture from the Pacific.

4) OUTCOMES

Based on LASSO data, it appears that the terrain is playing a role in initiating convection with convergence along the ridge of the Sierras de Córdoba range (Argentina) adding lift to initiate convection (Fig. 3b). Subsequently, outflow from the initial storms generates more convergence and lift to help initiate more convection.

c. Comparing Cold-Air Outbreak Conditions at COMBLE and the North Slope of Alaska (NSA)

Cold air outbreaks were the primary focus for the COMBLE group, with a specific investigation into the role of aerosol conditions at the various ARM sites. They also looked into planetary boundary layer characteristics as they relate to cloud structure (Seppala et al. 2024).

1) TEAM MEMBERS

- Jordan Eissner, University of Kansas
- Oye Ideki, Howard University
- Hannah Seppala, University of Maryland Baltimore County
- Shivesh Sharma, Cleveland State University
- Nirmal Mathew Alex, Florida Institute of Technology
- Ines Zabala, University of Granada

2) SCIENCE QUESTIONS

- How do aerosol (concentration, cloud condensation nuclei, ice nuclei) conditions vary between the sites?

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- How do boundary-layer (surface fluxes, turbulence) and cloud structures (cell type, characteristic size, phase) vary between the sites?

3) HYPOTHESES

- Cloud condensation nuclei and aerosol concentration will be smaller than average the day after cold-air outbreak (CAO) events due to precipitation scavenging.
- CAO index will be positively correlated with surface flux and wind direction/intensity.
- Clouds at the NSA will have different physical formation and be less glaciated due to younger age.

4) OUTCOMES

Sites have significantly different cloud types (stratiform at the NSA, cellular at COMBLE) and phase (mixed phase at the NSA, ice at COMBLE) due to location within CAO events.

Events sampled during COMBLE correspond with winds that are more northerly than average. CAO events in COMBLE can affect aerosol and CCN concentrations as well as aerosol activation properties. Both sensible and latent heat fluxes are correlated with the CAO index. Strong CAO events show higher surface fluxes and comparatively stronger diurnal cycles than weak CAO events (Fig. 3c). LES can be used to help explain cloud microphysical properties associated with differing event strengths and locations.

d. Aerosol Influence on Ground Snow Properties During SAIL

One group focused on the SAIL campaign (Feldman et al. 2023), a field campaign focused on the Colorado River Basin in Gunnison, Colorado. Their analysis utilized observations and simulations from the campaign to study changes in snow properties, specifically snow albedo, due to high aerosol loading events. Two case studies were used, 25 January 2022 and 3 April 2023, contrasting the earlier date that saw a high black carbon concentration event to the later date that saw more dust loading. This work is motivated by interest in aerosol-surface and aerosol-cloud interactions and their influence on the hydrology cycle, especially in a region of such ecological importance (Gasparik et al. 2024).

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1) TEAM MEMBERS

- Adrian Cortes Santos, University of Puerto Rico
- Jessica Gasparik, Brookhaven National Laboratory
- Joy Lai, Pacific Northwest National Laboratory
- Ryan Poland, University of Georgia
- Hayden Webb, University of Oklahoma
- Yan Xie, University of Michigan
- Maggie Zhang, Washington University in St. Louis

2) SCIENCE QUESTIONS

- Where do peak dust and black carbon events occur?
- How do these peaks correlate with changes in surface albedo/surface shortwave radiation?
- How does snowpack change around these events?

3) HYPOTHESES

- Decreases in local surface albedo will correlate with high aerosol loading events.
- Increased surface heating results in snowpack depth decrease following high aerosol loading events.
- The Weather Research and Forecasting (WRF) model does not implement aerosols in simulations and, therefore, could mispredict the snow radiation fluxes following aerosol events.

4) OUTCOMES

The team used the SAIL campaign measurements to perform a case study of three total events, including one control event and two high aerosol loading events. In situ measurements and back-trajectory model output were used to evaluate the number concentration and size distribution of aerosols and their black carbon levels. Analysis of longwave radiation measurements further confirmed that there was a high concentration of black carbon/aerosols in the atmosphere. Snow albedo decreases were observed in the two high aerosol loading events. Meanwhile, WRF simulations did not capture such decreases in surface albedo for the dust event (Fig. 3d). Because the WRF simulations used in this project

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did not incorporate aerosols, the team expects aerosols, along with other factors, can contribute to such a discrepancy between measurements and WRF simulations in terms of the snow-darkening effect of aerosols/black carbon. The hypotheses of this group were confirmed and showed that models like WRF that do not explicitly include aerosol entrainment, transport, and deposition will need corrections to their atmospheric radiation and surface albedo fields. Only with such corrections can they be fit-for-purpose for snow evolution, snowmelt, and land-atmosphere interaction studies in the winter and spring in complex terrain.

3. Conclusions and Feedback

Over 15 years ago, the atmospheric science community received a wake-up call on the need to augment its research advancements and scientific acumen with a strong commitment to education and workforce development (Charlevoix 2008). More recently, the community recognized the importance of combining traditional education approaches with new tools to assist this development (McNeal et al. 2022). However, there can be a tension between, on the one hand pushing into new frontiers of atmospheric science with the latest and greatest technology and science, and on the other fostering and growing the body of scientists who will ultimately advance the science much further than the current set of mid-career and senior scientists can. To that end, the importance of deploying state-of-the-art multivariate instrumentation in the field to advance the understanding of atmospheric processes cannot be understated. ARM regularly does this with its multiple, simultaneous observations of the atmosphere and surface using a wide range of technologies. With this advanced instrumentation, the question naturally arises as to what are viable approaches to atmospheric science education that entrain information available from such instrumentation.

With the 2024 ARM Summer School, an approach to atmospheric science education was taken that focused on in-person instruction followed by collaborative group research-focused activities, all supported by a strong foundation of open science tools. The results of the Summer School were shown here and indicated that the approach taken here was one that the atmospheric science community should strongly consider for field science educational advancement.

Finally, as part of its commitment to workforce development, the Atmospheric Radiation Measurement (ARM) user facility plans another summer school event in 2025, with the focus turning to the Bankhead National Forest site. To guide improvements, the team

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gathered feedback from this year's event, including how students received information about the application process and their experience at the event. Over 60% of students received information about the event from a professor or colleague. All outgoing students indicated that they now had a better understanding of the ARM user facility, data products, open-source computing tools and resources, with 90% of students indicating they strongly agree they left with a better understanding of ARM's capabilities and associated data products. Most students mentioned they most enjoyed the group projects, especially the hands-on experience and collaboration with others. It is planned that the group projects will continue to be a central pillar of the summer school. Key areas of potential improvement include instruction on collaborative project management using Github/Git and modifying the daily working lunch to a break, allowing students to step away from the content in the middle of the day. The ARM workforce development team looks forward to next year's event, where they will incorporate changes based on feedback and suggestions from this year's cohort, thereby improving the ARM Summer School for future participants. Students interested in future workforce development efforts should sign up for the ARM newsletter on https://www.arm.gov/.

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Data Availability Statement.

All materials from the event are openly available to the community, hosted on Github https://github.com/ARM-Development/arm-summer-school-2024.

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