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Report from the LASSO Expansion Workshop
Boulder, Colorado, May 2, 2019

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LASSO web page:
https:///www.arm.gov/capabilities/modeling/lasso/

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Executive Summary

The United States Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility held a workshop on May 2, 2019 to gather information on different weather scenarios that could be pursued for expanding the range of atmospheric processes that could be studied by the Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) data product. To date, LASSO has focused on the use of LES modeling to supplement ARM's suite of observations at the Southern Great Plains (SGP) atmospheric observatory for days that have shallow convective clouds. Input for the workshop was obtained from the community in the form of white papers that outlined additional meteorological phenomena that LASSO could pursue. Four white papers were submitted covering a wide range of phenomena of scientific interest to the DOE atmospheric modeling community and across the ARM spectrum of observation sites: maritime clouds, deep convection, clear-air turbulence, and arctic clouds. Topic experts were invited to the workshop to discuss each scenario in terms of the science drivers, feasibility of implementation (e.g., model configuration and needed observations), timing considerations, and any open issues related to the scenario that would need further investigation.

The science drivers for the proposed maritime scenario are the importance of maritime low-cloud feedback to climate and the sensitivity of these clouds to aerosol loading. The scenario was designed to be conducted at the Eastern North Atlantic (ENA) atmospheric observatory with a focus on precipitation processes for maritime shallow clouds and a secondary focus on aerosol-induced impacts on the clouds. A LASSO LES configuration for this scenario would use an over-ocean domain large enough to capture the relevant mesoscale variability, implying a domain size of between 25 and 60 km across. A doubly periodic domain would be simplest to use, but a limited-area modeling approach with a nested LES may be necessary to capture the mesoscale variability. An aerosol-aware microphysics scheme would be needed, which would require development of a new data product that provides aerosol profile information. Another critical measurement need is regional cloud and precipitation estimates from the X-band Scanning ARM Precipitation Radar (XSAPR2); due to data availability, this implies the potential simulation periods are limited to be during the Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) field campaign. Finally, a way is needed to estimate surface fluxes, which may be possible using sea surface measurements from a local buoy, satellite estimates, or numerical weather prediction models.

The proposed deep-convection scenario would address science drivers associated with convective initiation and the life cycle of initially isolated deep convective cells, prior to upscale growth. The focus of the LASSO LES would be convective cloud dynamics, such as thermals and cold pools, with a secondary focus on microphysical-dynamical interactions. The proposed scenario would focus on ARM Mobile Facility deployments: either on the Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign held in Argentina, and/or during the Tracking Aerosol Convection Interactions Experiment (TRACER) field campaign scheduled for Houston in 2021–2022. The model configuration would be a limited-area-model nested-LES approach using a 150-km-wide domain with 100-m grid spacing. To minimize cost, an initial ensemble of kilometer-scale grid spacing simulations would first be run to determine the best source of initial and lateral boundary

conditions for each case date, which would then be used for a smaller ensemble of LES simulations. Model development needs would include optimizing the LES output for particular periods or regions of the simulation to obtain the desired high-frequency model output for some variables. The observations used would have a strong focus on the thermodynamic state of the large-scale environment combined with radar data sets for clouds and precipitation.

The proposed clear-air turbulence scenario would focus on turbulence during cloud-free conditions with a particular focus on transitions, such as the evening decay of the boundary layer, and nighttime conditions. Workshop participants also expressed a strong desire to focus on surface heterogeneity and its impact on the boundary layer. Furthermore, nighttime conditions could optionally focus on the nocturnal low-level jet that is common at the Southern Great Plains (SGP) atmospheric observatory. Many of the meteorological conditions for this scenario occur at most ARM facility locations, and the SGP was used for discussion purposes at the workshop. The modeling approach for this scenario would require much higher resolution than the current shallow-convection scenario. Doubly periodic boundaries could be used if a homogeneous surface could be assumed, while treating science drivers focused on surface heterogeneity and the low-level jet would require a nested LES approach. Turbulence measurements would be the primary focus of the observational suite. Eddy covariance measurements from the SGP 60-m tower would play a central role along with regional surface-based meteorological and turbulence measurements. The Raman and Doppler lidars would be critical, and development of new products blending the two lidar measurements to retrieve profiles of thermodynamic fluxes would be valuable.

The proposed arctic scenario is motivated by a wide range of science drivers with a general focus on processes impacting arctic clouds. The scenario proposes to take advantage of the once-in-a-generation Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) mobile facility deployment during 2019–2020. This international, multi-institution campaign will embed an ice breaker into the arctic sea ice and let the ship drift with the ice for a year along with a network of observation sites surrounding the ship. This will provide detailed cloud and surface information for multiple seasons, including the polar night. Because of the more stable conditions in the Arctic, the proposed model configuration would use grid spacing around 20–40 m for a domain 30 km across and 4 km tall. Fewer options exist for obtaining large-scale forcings in this region, so they would probably come from the Fifth-Generation ECMWF Reanalysis (ERA5) product. Like the maritime scenario, the arctic scenario would need development of an aerosol profile data set. For some days, these observations could come from a tethersonde, which will be flown during portions of MOSAiC. Unlike the maritime scenario, the arctic scenario will need ice nuclei information in addition to cloud condensation nuclei. Other required observations will focus on the surface, boundary-layer, and cloud characteristics.

While secondary to science drivers and observation availability, computational cost is an important consideration. Overall cost is difficult to estimate since many small model configuration choices can easily combine to change the cost by an order of magnitude. The middle-of-the-range estimates for the scenarios, which represent the likely implementation, are roughly an order of magnitude more expensive than the current shallow-convection scenario on a per-simulation basis. These estimates can easily grow to two orders of magnitude more expensive depending on how many simulations are done per year and the chosen resolution. The current cluster used for the LASSO shallow-convection scenario can accommodate an additional scenario that is about four times more expensive, so choices will be necessary to balance computer availability and obtaining additional computing cycles.

The timelines for developing each scenario share a set of common requirements plus details specific to each scenario. All scenarios will require time to test candidate model configurations and develop suitable skill scores targeted at the science drivers. A lesson learned from the shallow-convection scenario is the value of a gestation period for identifying issues with observation data sets and modeling details. Several of the proposed scenarios could involve nested LES configurations, which will require adapting the skill score methodologies currently in use, testing related to boundary spin-up regions, and acquisition and implementation of high-resolution surface data sets for terrain height, soil use, and vegetation type. Development and hardening of new data products are the largest uncertainties impacting timing of the new scenarios, which is required to different degrees for all scenarios. For example, development of a retrieval for aerosol profiles is highly desirable for the maritime and arctic scenarios, but the necessary methodology does not yet exist. The most obvious timing limitation is the availability of newly collected data, which impacts the deep-convection and arctic scenarios the most. Processing of the CACTI radar data should be completed by the end of 2019, at which point LASSO developers could begin analyzing the data before use within a LASSO data bundle. The MOSAiC data will slowly become available for development use during the campaign, but non-ARM data will be subject to a data embargo for two years after the campaign ends and thus the bundles would not be released before that date. This logically delays implementation of the arctic scenario until at least 2021 for release in 2022 or later. The other three scenarios could start sooner, with the main limitation being whether any critical components would be missing from the observation suites.

Overall, workshop attendees expressed that all four scenarios have value for DOE and the larger atmospheric science community. It is hoped that all four will be implemented over time. This will lead not just to improved scientific understanding and models, but also to an improvement in the ARM facility as a whole through the focus the scenarios bring on developing and improving existing methods used for obtaining critical measurements.

Acronyms and Abbreviations

1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
4D	four-dimensional
AALCO	Aerial Assessment of Liquid in Clouds at Oliktok
ABL	atmospheric boundary layer
(AC^3)	Arctic Amplification: Climate Relevant Atmospheric and SurfaCe Processes and Feedback Mechanisms
ACE-ENA	Aerosol and Cloud Experiments in the Eastern North Atlantic
ACSE	Arctic Clouds during Summer Experiment
ACSM	aerosol chemical speciation monitor
ADI	ARM Data Integrator
AERI	atmospheric emitted radiance interferometer
AERIoe	AERI optimal estimation algorithm
ALCC	Advanced Leadership Computing Challenge
AMF	ARM Mobile Facility
AMIE	ARM MJO Investigation Experiment
ARM	Atmospheric Radiation Measurement
ARSCL	Active Remote Sensing of Clouds
ASR	Atmospheric System Research
BNL	Brookhaven National Laboratory
CACTI	Cloud, Aerosol, and Complex Terrain Interactions
CAFS	Coupled Arctic Forecasting System
CAP-MBL	Clouds, Aerosol, and Precipitation in the Marine Boundary Layer
CCN	cloud condensation nuclei
CIRES	Cooperative Institute for Research in Environmental Sciences
CLUBB	Cloud Layers Unified by Binormals
CN	condensation nuclei
COMBLE	Cold-Air Outbreaks in the Marine Boundary Layer Experiment
CRM	cloud-resolving modeling
CSAPR2	C-Band Scanning ARM Precipitation Radar
CuP	Cumulus Potential
DC	deep convection
DIAL	differential absorption lidar
DOE	U.S. Department of Energy
DOI	digital object identifier

DYNAMO	Dynamics of the Madden-Julian Oscillation
E3SM	Energy Exascale Earth System Model
ECMWF	European Centre for Medium-Range Weather Forecasting
ECOR	eddy correlation flux measurement system
ENA	Eastern North Atlantic
ERA5	fifth generation of the ECMWF reanalysis
ESRL	Earth System Research Laboratory
GASS	Global Atmospheric System Studies Panel
GCSS	GEWEX Cloud System Study
GEFS	Global Ensemble Forecast System
GEOS-5	Goddard Earth Observing System Model, Version 5
GEWEX	Global Energy and Water Exchanges Project
GISS	Goddard Institute for Space Studies
GoAmazon	Green Ocean Amazon 2014/15
GOES	Geostationary Operational Environmental Satellite
GPCI	GCSS Pacific Cross-Section Intercomparison
GTS	Global Telecommunications System
HiLAT-RASM	High-Latitude Application and Testing of Earth System Models-Regional Arctic System Model
HI-SCALE	Holistic Interactions of Shallow Clouds, Aerosols, and Ecosystems
HRRR	High-Resolution Rapid Refresh model
HSRL	high-spectral-resolution lidar
IASOA	International Arctic Systems for Observing the Atmosphere
IFS	Integrated Forecast System
INP	ice nucleating particle
INTERPSONDE	Interpolated Sounding VAP
IR	infrared
ISDAC	Indirect and Semi-Direct Aerosol Campaign
KAZR	Ka-Band ARM Zenith Radar
KAZR2ARSCL	KAZR2 Active Remote Sensing of Clouds VAP
KNMI	Royal Netherlands Meteorological Institute
LAM	limited area model
LASSO	Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation
LASSO-DC	LASSO-Deep Convection
LCL	lifting condensation level
LES	large-eddy simulation
LFC	level of free convection
LNB	level of neutral buoyancy
LW	longwave

LWP	liquid water path
MAGIC	Marine ARM GPCI Investigations of Clouds
MC3E	Midlatitude Continental Convective Clouds Experiment
MCS	mesoscale convective system
MERGESONDE	Merged Sounding VAP
MET	surface meteorology instrument clusters
MFRSR	multifilter rotating shadowband radiometer
MJO	Madden-Julian Oscillation
MOSAiC	Multidisciplinary Drifting Observatory for the Study of Arctic Climate
M-PACE	Mixed-Phase Arctic Cloud Experiment
MPS	meteorological particle spectrometer
MSDA	Multiscale Data Assimilation
MUCAPE	most unstable convective available potential energy
MWR	microwave radiometer
MWR3C	3-channel microwave radiometer
MWRRet	Microwave Radiometer Retrieval
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NEXRAD	Next-Generation Weather Radar
NOAA	National Oceanic and Atmospheric Administration
NSA	North Slope of Alaska
NWP	numerical weather prediction
NWS	National Weather Service
OLI	Oliktok Point, Alaska
PASCAL	Physical Feedbacks of Arctic Planetary Boundary Level Sea Ice, Cloud and Aerosol
PBL	planetary boundary layer
PDF	probability distribution function
PI	principal investigator
PNNL	Pacific Northwest National Laboratory
Polar-CORDEX	Polar-Coordinated Regional Downscaling Experiment – Arctic and Antarctic Domains
POPEYE	Profiling at Oliktok Point to Enhance YOPP Experiments
PPP	Polar Prediction Project
PSD	particle size distribution
RAP	Rapid Refresh weather forecast model
RHI	range-height indicator
RRTM	Rapid Radiative Transfer Model
RRTMG	Rapid Radiative Transfer Model for Global Climate Models

RWP	radar wind profiler
SACR	Scanning ARM Cloud Radar
SCM	single-column modeling
SEB	surface energy budget
SGP	Southern Great Plains
SGS	sub-grid-scale
SHEBA	Surface Heat Budget of the Arctic Ocean
SHOC	simplified higher-order closure
SONDE	balloon-borne sounding system
SST	sea surface temperature
SW	shortwave
TBS	tethered balloon system
TKE	turbulent kinetic energy
TOA	top of atmosphere
TRACER	Tracking Aerosol Convection Interactions Experiment
TSI	total sky imager
TWP-ICE	Tropical Warm Pool-International Cloud Experiment
UAS	unmanned aerial system
UTC	coordinated universal time
UV	ultraviolet
VAP	value-added product
VARANAL	Variational Analysis VAP
WBF	Wegener-Bergeron-Findeisen
WENO	weighted essentially non-oscillatory
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting Model
XSAPR	X-Band Scanning ARM Precipitation Radar
YOPP	Year of Polar Prediction

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1.0 Introduction to the LASSO Project

The ARM user facility has evolved into a vital repository of climate observations during its 25-plus-year existence. In this time, ARM has developed a clearer understanding of science drivers and methods to increase the usefulness of its data by employing new technologies, and by having leadership willing to risk employing new approaches (Turner and Ellingson 2016). As an observation-based user facility, ARM traditionally has not generated simulation data from numerical models. However, from near ARM's inception, there has been a realization that certain types of models could complement ARM observations to produce a more impactful data suite for researchers — in particular, when the model is constrained by observations from the facility.

In 2012, DOE and ARM leadership convened an international group of scientists at the US/European Workshop on Climate Change Challenges and Observations, at which the topic of modeling was broached to fill gaps and expand the scope of ARM's spatially limited observations. Extensive use of ARM data to support single-column modeling SCM) and cloud-resolving modeling (CRM) had occurred prior to that point; however, this work typically was at the single-investigator level and focused on specific cases or short periods that did not take advantage of ARM's continuous observations (vide Krueger, Morrison, and Fridlind 2016; M. Zhang, Somerville, and Xie 2016). High-resolution models clearly have provided a key link from the local-scale measurements to the scales needed by climate and forecasting model developers, yet the case-study nature of the modeling has limited its full potential. The resulting workshop report suggests operational large-eddy simulation (LES) output "be used as powerful additional 'virtual observations' of processes that cannot or only partly be observed" (Mather et al. 2012). The suggestion was partially motivated by the demonstration of the Royal Netherlands Meteorological Institute (KNMI) Parameterization Testbed (Neggers, Siebesma, and Heus 2012), where a LES model was routinely run alongside the detailed atmospheric observations taken at Cabauw in the Netherlands. The KNMI Testbed ran an LES model every day for the Cabauw location and provided a web-based interface for users to interact with the data.

Shortly thereafter, a targeted workshop was held to specifically discuss the option of implementing high-resolution modeling at ARM's Southern Great Plains (SGP) facility in Oklahoma. The associated workshop report suggested performing a pilot study to develop an appropriate modeling configuration and to answer open questions related to taking on this type of endeavor, such as what type of forcing data to use for the LES (DOE Climate and Environmental Sciences Division 2014). This seed resulted in a 2014 request for white papers from DOE national laboratories to suggest ways to implement high-resolution modeling in the context of shallow convection at the SGP with a goal of better coupling ARM observations and modeling activities. A two-year grant was subsequently awarded for the LASSO Pilot Project, led by William Gustafson and Andrew Vogelmann.

During this two-year pilot, which was completed in 2017, the vision for LASSO solidified into the resulting combination of forcing data, LES ensemble, observations, skill scores, and methods for data discovery and delivery. The current implementation of LASSO for continental shallow convection at the SGP is described in Section 2.0, with full details available via https://www.arm.gov/capabilities/modeling/lasso and data bundles available for download via the LASSO Bundle Browser, https://adc.arm.gov/lassobrowser. In short, LASSO provides an ever growing library of cases where LES input and output are produced for an ensemble of forcing data sets combined with a suite of relevant ARM observations used to generate diagnostics and skill scores that are made available to users via a merged file structure referred to as "data bundles." Appendix A.1 provides a summary of relevant LASSO website links and technical reports written to date.

1.1 Long-term Vision for LASSO

Presently, LASSO produces simulations and data bundles containing a suite of observations and model input/output for continental shallow convection over ARM's SGP atmospheric observatory. To date, the LASSO library consists of 78 cases of shallow convection during spring and summer from 2015–2018. The current intent is to continue increasing this library as new shallow convection days occur at the SGP for at least the next several years. Much of the value provided by LASSO is the capability to go beyond a single-case-study mentality to using many cases to generate statistically robust analyses.

From its inception, the ultimate goal for LASSO has been to produce observation–model synergy across the ARM facility and not just for a single cloud regime at one location. The *ARM Decadal Vision* (U.S. Department of Energy 2014) calls for expanding LASSO beyond the SGP. The original plan was to next tackle the North Slope of Alaska; however, subsequent input from the community has led ARM to consider other alternatives. Expanding from the prototype shallow-convection scenario to producing high-resolution simulations for all ARM sites and meteorological conditions is untenable due to limited staffing and resources. Therefore, the suggested approach is to expand incrementally within available resources to simulate several scenarios simultaneously over the next several years.

This document describes the outcome of the LASSO Expansion Workshop held May 2, 2019 to gather information on different scenario options and the data collection process that led up to the workshop. Four scenarios will be described that are considered to be the highest priority at this time: maritime clouds, deep convection, clear-air turbulence, and arctic clouds. Before these scenarios are discussed in Section 3, Section 2 describes the current shallow-convection scenario as an orientation to what a successful scenario looks like, its usages, and lessons learned.

2.0 The Current Shallow-Convection SGP Scenario

2.1 Scenario Description

The shallow-convection scenario has been run for four seasons so far, and the case library consists of 78 days with shallow convection at the SGP. The configuration and approach for this scenario were chosen based on a combination of science drivers and practicality. Because routine production of numerical model data is new within the ARM infrastructure, a scenario was desired that was known to function well such that the details of the modeling would not be so difficult that they would require much of the available development resources. Since LES has been used for shallow convection for many decades, this cloud regime was an excellent option for a starting point because the overall model configuration could be anticipated based on previous experience. This then permitted more effort to be committed to determining how to integrate modeling data into ARM's storage, discovery, and delivery systems. For example, the LASSO Bundle Browser has been developed to make it easier for users to find relevant simulations for the particular applications, which is a very different approach than is available for searching the full archive of available ARM observations with the Data Discovery web interface. Also, a behind-the-scenes effort is ongoing during 2019 to automate much of the LASSO processing to make it cheaper and enable simultaneous handling of multiple LASSO scenarios.

The science drivers motivating the shallow-convection scenario focus naturally around the processes that drive shallow convection and the difficulty for weather and climate models to simulate shallow-cloud processes. Shallow convective clouds are small enough that even kilometer-scale atmospheric models, which are used for current state-of-the-art weather forecasts and are the aspirational scale for future climate models such as the DOE Energy Earth Exascale System Model (E3SM), cannot reproduce the radiative and mixing effects of these clouds at the resolved scale and instead must parameterize the impacts of these clouds on the resolved scales.

Different methods have been proposed to do this parameterization, such as the Cloud Layers Unified by Binormals (CLUBB) (Golaz, Larson, and Cotton 2002; Larson et al. 2012; Thayer-Calder et al. 2015) and Cumulus Potential (CuP) (Berg et al. 2013; Berg and Stull 2005) schemes. Both schemes rely on the use of probability distributions of small-scale processes that are difficult to measure. Thus, it is difficult to establish some of the parameters used by the two approaches and the schemes are inherently difficult to verify with routine observations, at least for some of the important underlying process representations. However, very high-resolution simulations, such as the LES methodology used with LASSO, are one way to obtain realistic representations of the necessary values, such as turbulent fluxes of momentum, energy, and moisture. Identifying how these values change for different atmospheric states is an example of how having a library of cases is important for LASSO.

Another science driver is the need to have three-dimensional (3D) volumes of the atmosphere to use for developing and testing retrieval methodologies. A large number of the ARM instruments are geared toward the use of remote-sensing retrievals for atmospheric conditions because in situ measurements are impractical for the time and spatial resolutions often needed by scientists. Examples include radars that can be used to retrieve cloud droplet information, cloud phase, and wind velocities. Likewise, lidars provide information about cloud-base heights, profiles of aerosol properties, thermodynamic state, and momentum fluxes. Understanding the representativeness of these retrievals for the region surrounding the SGP site and the ability of the retrievals to accurately reflect what they are estimating is often difficult. The LASSO LES simulations can be combined with instrument simulators to implement the retrieval methodologies within the virtual environment such that knowledge can be gained for how to improve the methodologies when used operationally in the real world.

The model configuration used for the LASSO shallow-convection scenario is a traditional LES approach with doubly periodic boundaries, profile-based large-scale forcing applied as tendencies to the domain, and specification of spatially homogeneous surface fluxes at the model's lower boundary. Details regarding the domain and physics parameterizations settings can be found in Table 2 in Appendix A.2.

A unique aspect of the LASSO approach is the use of an ensemble of large-scale forcings to generate an ensemble of LES realizations for each simulated case date. It has been found that uncertainty in the large-scale forcings is a significant contributor to accurately simulating a given day, and thus the use of a range of forcing data from different sources increases the likelihood of obtaining a realistic simulation for a given case. As outlined in Gustafson et al. (2018), eight forcing configurations are used for the shallow-convection scenario as summarized in Table 3 in Appendix A.2.

Users can then decide whether to use multiple ensemble members for a given case or choose one that best matches observations depending on their particular research application. This decision process is simplified by providing the observation suite alongside the LES output along with a set of skill scores that evaluate model behavior for a range of variables relevant for shallow convection.

Compiling a suite of observations to accompany the LES is a critical component of LASSO, as this both highlights available ARM measurements for users as well as provides the data necessary to evaluate the simulations. The values from these observations are provided to users within the LASSO data bundle files and the data is also used within the Bundle Browser to show time series and scatter-plot comparisons of the LES output versus the observations combined with skill scores that quantify the comparison. The suite of measurements and retrievals included in the shallow-convection data bundles are listed in Table 4 in Appendix A.2.

2.2 Usage of LASSO

To date, four research papers plus a meeting summary have been published using LASSO data (see Appendix A.3), with several other papers known to be in progress. These articles represent a varied range of applications of the LASSO data. The uses closely align with how LASSO was originally envisioned to add value for research applications. We expect the use of LASSO data to grow over the coming years as its existence becomes more widely known and examples of its use begin percolating through the literature. The following summarizes the currently cited usage of LASSO data:

- Mariko Oue et al. (2016) performed a radar retrieval study that used a LASSO LES cloud field as a proxy for real-world shallow convection to quantify the impact of different cloud-radar scan strategies on the ability to accurately quantify the cloud fraction profile.
- Wayne Angevine et al. (2018) used LASSO in a parameterization evaluation study where the LASSO LES served as a benchmark for the boundary-layer and cloud characteristics. The LASSO forcing data were used to drive a single-column model containing the parameterization being developed.

- Roel Neggers, Griewank, and Heus (2019) used the LASSO large-scale forcing data in a study that examined the spatial structure of shallow clouds and created a metric to quantify the cloud organization.
- Jerome Fast et al. (2019) compared LASSO simulations to observations during the Holistic Interactions of Shallow Clouds, Aerosols, and Ecosystems (HI-SCALE) field campaign for information not normally available in the LASSO data bundles, such as droplet size distributions from aircraft flights.
- An encouraging use of LASSO was shared in the meeting summary of the 2018 ARM Summer Training and Science Applications Event held in Norman, Oklahoma in July 2018 (Ghate et al. 2019). This meeting focused on training 24 graduate students and early career scientists in the details of using ARM data, remote sensing, and modeling to understand clouds and aerosol. Part of the time was spent doing hands-on LES modeling, with users first selecting cases by using the LASSO Bundle Browser and then running their own simulations that were initialized and forced by the LASSO data. This was an excellent way to demonstrate to the students the sensitivity of simulated shallow convection and provide them with experience comparing observations with simulations.

In addition to the published LASSO uses, questions occasionally are posed to the LASSO development team regarding other applications of the LASSO data. Inquiries that have been raised include using LASSO to help understand the impacts of 3D radiation and ways to use LASSO in the context of machine learning.

Another tangible measure of LASSO visibility is its mention in workshops and conferences. For example, the Understanding Clouds and Precipitation 2019 (UCP2019) conference in Berlin, Germany in February 2019 requested talks on “technical advances for simulating, computing and observing clouds and precipitation” with reports from LASSO specifically requested.

Download statistics for the period September 2017 through September 2018 are shown in Table 5 in Appendix A.4.

2.3 Lessons Learned

Working with the shallow-convection scenario over the past several years has resulted in many insights and lessons learned that would be useful to consider when expanding LASSO to include additional scenarios.

1. Managing user expectations requires clearly communicating science drivers and what the observations and modeling can and cannot provide for a given scenario. LASSO users come from diverse observation and modeling backgrounds and thus do not always readily comprehend the scope and representativeness details of what is included in the data bundles. A lot of user support has occurred around these sorts of topics. For example, the LES methodology employed for the shallow-convection scenario implies that every column in the model domain is statistically identical and, thus, one cannot conceive the spatial size of the domain as equating to the same distance over the SGP region. Instead, the model should be understood to produce the

cloud population contained within the region roughly the scale of that used to generate the large-scale forcing.

2. The multi-year nature of LASSO has been important for understanding model biases and identifying issues with both the observations and the model, as this discovery process tends to be iterative. This should be considered when choosing expansion scenarios and motivate longer scenarios where possible. For example, having multiple seasons of simulations has permitted us to identify calibration errors in a new temperature sensor that would otherwise have been relegated to model bias if only a single season of cases were available. If a shorter scenario is considered, sufficient time is needed for a thorough analysis of the available data. In short, time is needed for the learning curve involved to understand the observations and modeling for a new site before moving to the next scenario.

3. Estimating the cost of a scenario requires paying careful attention to potential automation, and particularly to portions of the workflow that would limit automation. For example, a lot of time has been spent manually processing and quality-controlling observations for the shallow-convection scenario because several of the required observations are not yet routinely produced.

4. Production readiness of observations can—in a practical sense—only be expected from tried-and-true instruments or retrievals. Application of any new instrument or retrieval requires dedicated resources to feasibly provide high-quality data for beginning use within LASSO. The shallow-convection scenario has been slowed considerably by needing to use data sets that were initially thought to be robust but later turned out to not provide the accuracy needed, and which therefore required substantial quality control prior to use or were still in flux because they were still being developed. This is particularly important for new instrumentation and retrievals. For example, the ARM implementation of the atmospheric emitted radiance interferometer (AERI) optimal estimation algorithm (AERIoe) did not begin until after LASSO began and more than a year was needed to resolve issues. The algorithm was intended to use data from the new three-channel microwave radiometers (MWRs) installed at the boundary facilities in anticipation of LASSO, but the MWRs encountered calibrations issues that are still being resolved. The AERIoe retrieval algorithm was also new to production and required debugging over an extended period. These complications were unforeseen as, generally speaking, the algorithm and the MWR instrumentation already had an established pedigree coming into the process, yet a lot of additional effort was needed to evaluate products and develop workarounds.

5. Developing a user interface to search for relevant data bundles has been extremely popular. The LASSO Bundle Browser is often mentioned as a powerful tool that greatly simplifies the user introduction to LASSO and quickens the data delivery process. Careful thought will be needed as multiple scenarios become available so that users clearly understand what they are searching for and are able to search both within and across scenarios in a scientifically useful manner. There also remains user interest in having the LASSO team identify the “best” simulations.

6. Development of LASSO software should formally add an additional step between the “research” code development and the point where it is passed off to personnel who work on implementation within the ARM system. LASSO has involved writing a number of new codes to test aspects of a model, process observations, or coordinate aspects of the workflow. At the time, it was a moving target, so speed and accuracy were the highest priorities to quickly assess

different options while meeting release deadlines. Time needs to be allocated to clean up and embed comments to document the final “winning” approaches/codes. Doing this as soon as possible is both a risk management priority, to safeguard against unexpected personnel changes, as well as a means for simplifying passage of the code to other developers for production.

7. The long-term maintenance of LASSO is an issue that needs consideration within the scope of changes to underlying data sets that feed into the LASSO data bundles. Over the years of operation, multiple instances have arisen in which issues have been identified in the input data, the way the data was processed, or the LES model. This has resulted in the need to reissue data bundles for some cases. In other cases, the changes were small and would minimally impact users, so data bundles were not reissued. However, it would have been useful to have the ability to issue data quality reports for the impacted data bundles. Currently, this is not possible with LASSO because it is not a traditional datastream. An investment needs to be made to enable data quality reports for LASSO in a way that users will understand known issues for data bundles that the users have downloaded. An easy way to re-release data bundles also needs to be developed.

8. The impact of LASSO can be enhanced if it were possible for users to easily run a subset of the LASSO codes outside of the ARM computing infrastructure. So far, the LASSO development team has already had two requests for the LASSO software to be used outside of ARM to generate LASSO-like diagnostics and skill scores. One would be for integration into the Global Model Test Bed, https://dtcenter.org/eval/gmtb/, being developed to evaluate the next-generation National Weather Service (NWS) forecast model. As the code becomes more dependent on the ARM Data Integrator (ADI) software library, the more difficult it will become for users to easily use the LASSO software on their own machines. Additionally, documentation of the code itself, as opposed to the higher-level documentation currently made available, would be needed to assist users. While some of these aspects have been discussed, the path and resources to practical open-use LASSO software is uncertain. At the moment, the biggest need in this area is to determine the best approach for making the code available to meet data policy requirements for users publishing with LASSO data, whether or not the code would be functional.

3.0 Proposed LASSO Scenarios

Collection of information needed to make the LASSO expansion decision has been ongoing for over a year and culminated in an Expansion Workshop held on May 2, 2019 in Boulder, Colorado. A timeline is provided in Appendix A.4 that highlights important steps taken to reach out to the broad community of potential LASSO users to seek guidance that would fulfill ARM’s intentions for LASSO. A key step occurred in early 2019, when white papers describing potential LASSO scenarios were requested from the community. To ensure that scenarios were proposed for what were high-priority possibilities based on feedback from the LASSO breakout session from the 2018 ARM/Atmospheric System Research (ASR) principal investigator (PI) meeting, three teams were recruited to write papers on scenarios for arctic clouds, deep convection, and maritime clouds. Additionally, a clear-air turbulence paper was contributed. The invited writing teams, which initially consisted of four members each, reached out to the community to gain an overall consensus and the author lists represent the larger effort totaling 35 coauthors. The LASSO Expansion Workshop was devoted to discussing the merits and options for each scenario (see the agenda in Appendix B.1). It was clear from the presentations and the associated discussion that all of the scenarios have important science drivers and potential for enhancing ARM observations through the addition of the modeling.

This section provides the guiding principles used to focus the LASSO expansion process, followed by high-level descriptions of each scenario and how they could be implemented. More detailed information and discussion of options are available in the full white papers, which are available in Appendix C. The ensuing order of the scenarios reflects the order of their presentation during the workshop. Following the summaries describing each of the four scenarios, additional analysis extracted from presentations and whitepapers is presented, including computational impacts. This is followed by conclusions on key considerations for scenario implementation and constraints on timing drawn from the workshop discussion.

3.1 Guiding Principles for Expanding LASSO

The approach taken to decide how to expand LASSO has been driven by the following primary guiding principles:

1. The first, and highest, priority is that *the expansion decision should be science-driven* with whatever is chosen being done because it serves high-priority science needs of ARM/ASR and serves a broad user community. Ideally, the chosen scenario(s) should serve multiple science needs and provide information that would not otherwise be easily available to the community without ARM providing it.

2. *ARM is fundamentally an observation-based user facility*. Any numerical modeling ARM undertakes should be done to add value to ARM's observations and guide users to increased ARM data usage. The LASSO effort is not solely for the sake of the modeling. This motivates questions such as how does the modeling enhance understanding of the observations? How does the modeling provide context to the observations? Does the modeling elucidate connections between disparate observations? How can the modeling enable analysis for improving observation strategies?

3. *The computational cost should not be the foremost criteria when choosing a future scenario*. However, one must be practical and work within reasonable computational limitations. Likewise, the labor to generate the data bundles should be as automatable as possible to minimize production costs. Ultimately, the overall cost must be considered within the perspective of the overall ARM budget and priorities of the targeted science drivers.

4. *Any new scenario needs to be timed such that the modeling effort does not precede necessary observational data sets*. Some proposed scenarios may need additional instruments installed to obtain important data or need additional development of value-added products or retrievals based on existing observations. While anticipation of scenario needs can serve as a focal point for providing the new instruments or methodologies, it is inefficient to invest significant effort into the modeling until the necessary observations are routinely available and considered robust. The implications of this principle are to take into consideration the timing of potential scenarios and to increase or decrease relative priority based on what will be necessary to provide operational products to users.

3.2 Maritime Clouds Scenario

The proposed maritime clouds scenario entails producing LES simulations of maritime shallow clouds at the ARM Eastern North Atlantic (ENA) atmospheric observatory with a particular focus on precipitation processes and a secondary focus on aerosol-induced impacts on the clouds. It is well known that marine low clouds are the largest source of diversity in climate change projections and that the associated cloud processes need improvement in climate models. Of particular interest is the tendency for models to overestimate the frequency of light precipitation and likely underestimate its strength. ARM's extensive suite of instruments at the ENA provide abundant information to address these issues and having a library of LESs will enhance the ability to interpret the observations and improve climate model biases.

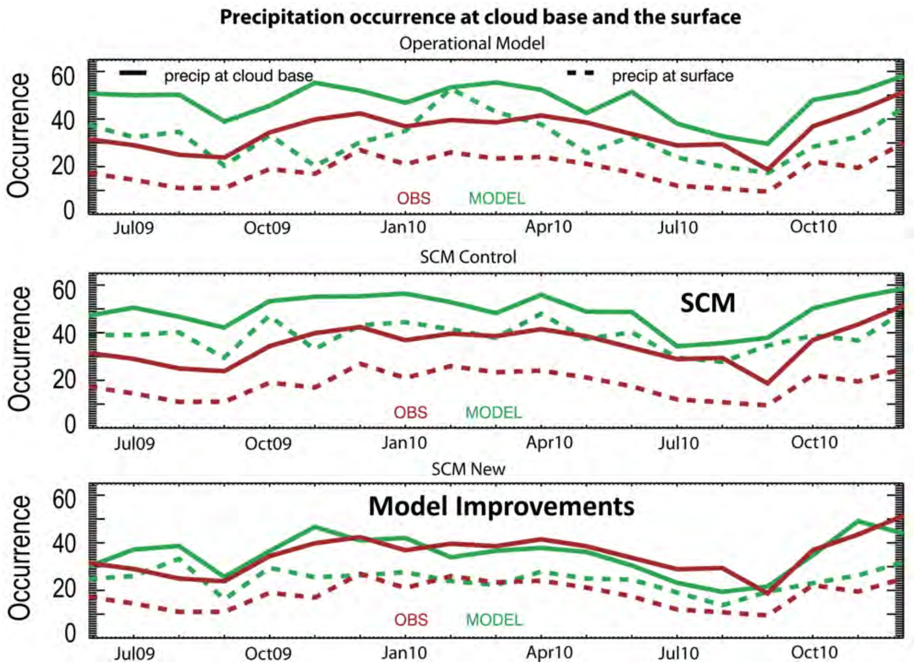

Figure 1. An example of the usefulness of ARM's data at Graciosa Island for contributing to the science areas of the proposed maritime scenario based on a study by Ahlgrimm and Forbes (2014). Monthly mean precipitation occurrence at cloud base (solid) and the surface (dashed) during the Clouds, Aerosol, and Precipitation in the Marine Boundary Layer (CAP-MBL) campaign for ARM observations (red) and the IFS model (green). (a) Comparison for the global operational IFS model. (b) Comparison to the ECMWF SCM model. (c) Comparison to the SCM model after making improvements. Derived from Figures 1 and 6 of Ahlgrimm and Forbes (2014). ©2014 American Meteorological Society.

Four focal science questions have been used to organize the maritime scenario:

1. How do even relatively thin clouds at the ENA site produce detectable precipitation?
2. Is low-cloud precipitation at the ENA site controlled primarily by the availability of condensate, and how sensitive is it to cloud droplet concentration?

3. How do meteorological controls, such as wind speed and turbulent mixing in the planetary boundary layer (PBL), affect condensate and precipitation?

4. How strongly are cloud droplet sizes and concentrations related to aerosol properties measured at the surface and what cloud processes are important for controlling the relationship?

The model configuration proposed for this scenario entails using LES with an oceanic domain for cloud cases selected based on the wind coming from the west and/or north. This avoids issues related to the island impacting the cloud field and simplifies the modeling approach. Periodic lateral boundaries combined with large-scale forcing derived from the fifth generation of the ECMWF reanalysis product (ERA5; https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5) would capture the background flow field and synoptic conditions. The lower boundary could either use specified fluxes or prescribed sea surface temperature (SST). Horizontal grid spacing would be 50 m and vertical grid spacing would be 10–20 m within the boundary layer. Because aerosol impacts on the clouds are important in this environment, aerosol-aware microphysics would be used combined with a prescribed, observationally derived aerosol profile.

The domain width was a subject of debate since the width would need to be sufficient to encompass relevant mesoscale variability, such as pockets of open and closed cellular convection. Nominally, the domain width will need to be 25 km or potentially up to 60 km for open cells. This is partially a function of how well the large-scale forcing imposes the mesoscale variability on the LES and the ability of the LES to spin up accurate representations of the cloud conditions. To avoid the scale-separation issues inherent in using uniform large-scale forcings with periodic boundaries, a proposed alternative was to use a limited-area model configuration with a nested LES approach with the ERA5 providing temporally and spatially varying boundary conditions. Testing will be required under varying open- and closed-cell conditions to identify whether periodic boundaries are sufficient or if nesting will be needed. The domain size would likely be closer to 60 km for a nested approach to capture the relevant mesoscale structures. However, this would permit a more straightforward modeling approach with less assumptions by avoiding the step to convert the ERA5 into a large-scale forcing. Evaluation will also be needed to determine the best handling of pre-existing cloud at model initiation, which could be influenced both by domain size and boundary condition type.

The relevant data to include within a LASSO data bundle is extensive, as detailed in the maritime white paper (Appendix C.1, Table 7). The general theme of the observations is the need to quantify the cloud state, areal precipitation characteristics, boundary-layer turbulence, and the aerosol characteristics. Of the measurements, the critical ones include areal drizzle at both the cloud base and surface from the scanning XSAPR2 (Figure 2), measurements of SST or surface fluxes, an aerosol profile of the particle size distribution at a minimum along with hygroscopicity if possible, and detail to put the simulations within the context of the mesoscale variability.

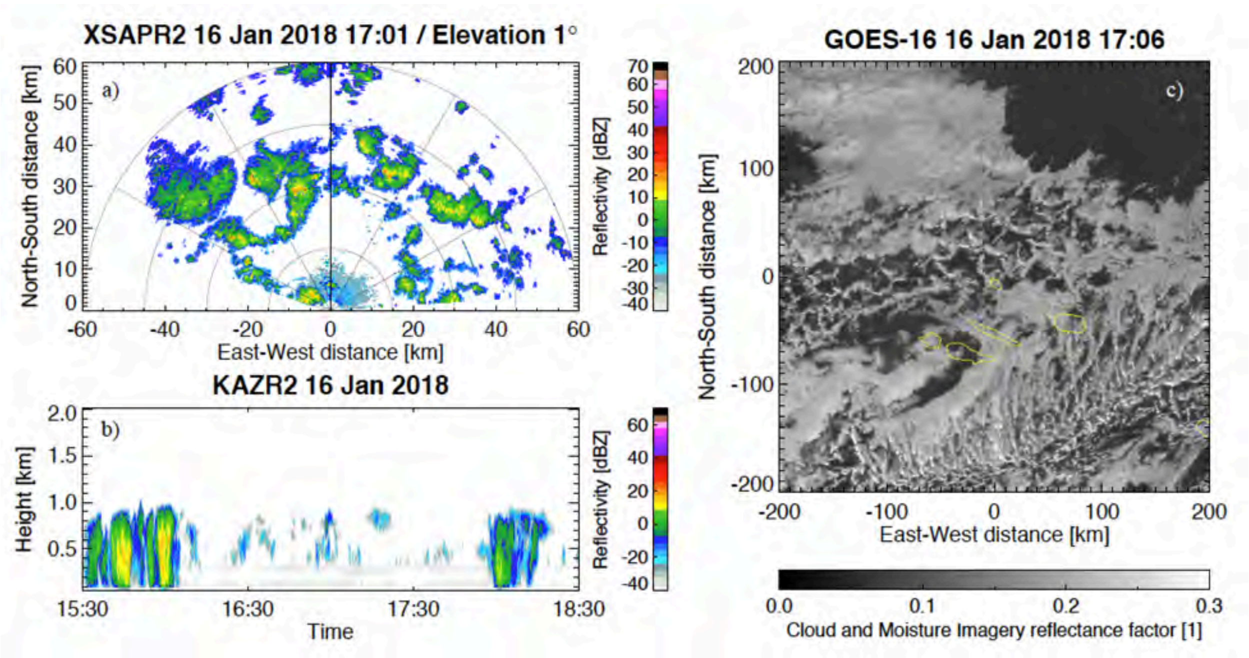

Figure 2. An example of ARM radar reflectivities (dBZ) from the XSAPR2 and KAZR2 radars on Graciosa on January 16, 2018 during ACE-ENA (left) alongside the corresponding Geostationary Operational Environmental Satellite (GOES)-16 visible image for the same time (right). Yellow contours indicate the Azores islands.

Handling of the lower boundary was discussed extensively regarding the two primary approaches that could be used to inform the model. Potentially, buoy measurements could provide bulk meteorological measurements of near-surface temperature and moisture over the ocean that could then be used to derive surface fluxes. There may be a buoy with available data, but the ability to accurately use this data to derive surface fluxes was unclear. An easier approach would be to provide the LES with observed SST from a buoy, satellite retrievals, or ERA5 and then permit the model to calculate its own surface fluxes. The method that would be more accurate would depend upon the accuracy of the surface model in the LES and the quality and type of data that could be obtained over the nearby ocean. A mini-intensive operation period was proposed to test the various approaches.

Given the importance of aerosol on cloud formation in this maritime environment, accurate representation of the background aerosol profile needs to be obtained to inform the LES. Surface measurements of aerosol size and composition are routinely made on Graciosa, which could be used as a starting point to make an informed estimate of aerosol conditions at cloud base. The difficulty would be extrapolating the surface data upward. Doing this would require using lidar measurements combined with assumptions regarding aerosol hygroscopicity and particle swelling due to changes in relative humidity throughout the boundary layer. While this introduces uncertainty, it is currently the best-known approach. An additional complication is that sea-salt particles are not routinely measured at ENA. The aerosol-profile product would need to be developed for the maritime scenario.

Overall, with the exception of the data issues noted above, the modeling approach for the maritime scenario is somewhat straightforward to implement. Because the XSAPR2 is currently not functioning, the most practical simulation period to choose would be for the ACE-ENA field campaign, which occurred from June–July 2017 and January–February 2018. This period also has the advantage that the data sets have already been generated by the Site Science Team and have already undergone initial evaluations, which will reduce LASSO costs related to data quality issues.

3.3 Deep-Convection Scenario

Deep convection has been a longstanding problem for weather and climate models since the early days of general circulation models. However, computers are beginning to be able to resolve small-scale details of convective cells within the context of larger convective environments. Combining these types of simulations with detailed observations has the potential to open up new areas of understanding of convective processes and improved parameterizations for models. ARM is uniquely situated to provide the necessary observations, and a LASSO deep-convection scenario would provide a library of complimentary simulations for researchers to draw from.

The proposed science drivers for this scenario focus around the early stages of deep convective initiation and the life cycle of isolated deep convective cells, prior to upscale growth. This is both a science-driven and practical choice. There are many processes to be understood during this portion of the convective life cycle and including larger, organized convection would significantly increase the domain size. The primary processes to drive configuration choices would be convective cloud dynamics, such as thermals and cold pools, with a secondary emphasis on microphysics-dynamics interactions.

Contemplation of a deep-convection scenario inevitably leads to consideration of what compromises need to be made to make such an endeavor affordable. By its nature, deep convection requires simulations over large areas and the need to resolve detailed convective-cell dynamics implies high resolution. Thus, compromises are necessary, but these need to be made within the context of the intended scientific drivers of this scenario. The proposed approach for the deep-convection scenario is unique compared to the other scenarios with the goal of balancing costs. The first compromise is the practical consideration of performing a smaller number of simulations per year, potentially around 10. The second is to use coarser kilometer-scale grid spacing to identify candidate days for LES modeling. The goal is to use ensembles of mesoscale simulations with members generated from a range of forcing data sets to narrow down which initial and boundary-condition data sets perform best for candidate days. Potential forcings could come from ERA5 ensemble members as well as the Global Ensemble Forecast System. Then, once adequate model behavior is verified with a grid spacing of 2.5 km, LES would be done only for the best input data. This will increase the odds of the LES generating realistic convection, particularly the early stages of convective initiation, for use alongside ARM observations.

The LES domain is expected to be about 150 km wide, which would be large enough to simulate convective initiation and the early stages of convective system life cycles. Horizontal grid spacing would be 100 m to capture the bubble-like behavior within convective cells. A bulk microphysics parameterization, such as the Thompson-Eidhammer aerosol-aware scheme (Thompson and Eidhammer 2014), would be used since the cost of bin microphysics was deemed excessive for the potential benefit.

Observations used for this scenario would entail environmental profiles of the large-scale meteorological environment as well as in-cloud details, such as condensate amounts and hydrometeor identification. Identification of candidate forcing data sets would use metrics derived to estimate the general accuracy of convection timing and location, such as first echo and echo-top heights, and satellite images to assess the bulk structure of the storm. LES evaluation and supplementary observations would consist of probability distribution functions (PDFs) of precipitation, convective fraction, and echo-top heights. Other important information would be cloud fraction profiles, 3D vertical velocities, and regional precipitation. Scanning radars would play a large role in many of these measurements, as well as lidars, disdrometers, and soundings.

Three potential locations were discussed for deploying a deep-convection scenario. The availability of scanning radar data combined with the timing of campaigns will likely determine which location is chosen. Scanning C-band radar has been deemed a critical observation to capture cloud core information as well as nascent cloud features. Because of this, combined with the lack of frequent convective events forming near the SGP, the SGP location is not a practical choice at this time, although it could be considered in the future if the scanning cloud radars routinely operate. A more likely candidate would be the CACTI field campaign that occurred in Argentina from October 2018 through April 2019. Eighty deep convective events have been identified from this campaign as well as many other types of cloud conditions that could be simulated. Processing of the CACTI radar data is in progress and is expected to be completed later in 2019. In addition to CACTI, the TRACER field campaign in Houston, scheduled for April 2021 through April 2022, is another strong option for a deep-convection scenario when looking over a longer time horizon.

Figure 3. The primary instrument cluster for CACTI during the first ARM Mobile Facility (AMF1) deployment in Argentina. In the background is the Sierras de Córdoba mountain range that contribute to frequent strong deep convection in the region.

Potential difficulties with the deep-convection scenario involve the inherent limited predictability of convection, incorporating radar data into an operational LASSO product, and handling the large domains, which involves both computational and data management issues. The predictability issues will be partially mitigated though selection of the forcing data via the coarser simulations. However, this does not guarantee the LES will produce clouds in the same locations as the coarser simulations. Unlike the shallow-convection LES in the original LASSO configuration, the deep convective clouds within the LES domain will not be a statistical sample of the regional clouds and will instead be more deterministic in nature due to the large size of these clouds and their strong ties to local terrain features and synoptic forcing. This potentially complicates evaluations because we cannot lean on statistical sampling to compensate for a finite observing network, so more complicated phase space or object-oriented evaluation strategies may be needed. Also, as the nascent clouds grow into larger cloud systems, any small errors will propagate and lead to growing discrepancies between reality and the simulations.

Incorporation of radar data into LASSO will require development effort to incorporate a radar simulator into the workflow. Additionally, the basic production radar products will need to be processed into more research-appropriate forms, such as converting them to rectilinear grids instead of the native polar grids and doing retrievals for physical variables, such as vertical velocity.

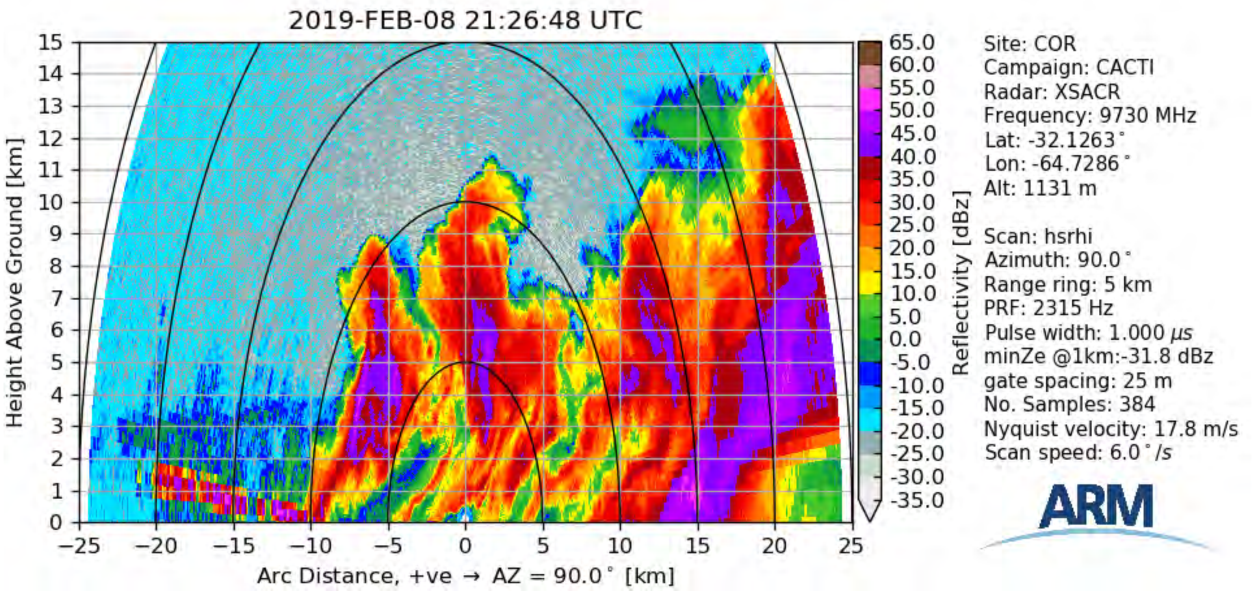

Figure 4. Range-height indicator scan of reflectivity (dBz) from the X-SAPR radar at CACTI on February 8, 2019, 21:26 UTC. Ground clutter in the left side of the image indicates the presence of the mountains, which trigger convective cells that grow as they propagate downwind.

The domains for the deep convection will be about 150 km across with 100-m grid spacing, which equates to 1500 points in each horizontal dimension. This size domain can easily use up to around 10,000 cores at a time for computation and the resulting output will be large. Meeting the science driver of understanding convective cell behaviors will require frequent output, potentially sub-minute. Work will be needed to determine the appropriate compromises to make in archiving model output, such as only outputting a portion of the domain, saving some variables more frequently than others, and only doing the highest-frequency output for certain portions of the simulation period.

Ultimately, the library of deep-convective simulations that ARM would produce via the deep-convection scenario would be unique and highly valuable to the research community. This is an undertaking that few, if any, other research groups could accomplish. ARM would be filling a void in the availability of cell-resolving deep-convection simulations coincident with detailed 4D data sets of specific real-world convective events. To date, most available simulations of this precision are for one or a small number of cases, often for idealized conditions where model biases are harder to identify.

3.4 Clear-Air Turbulence Scenario

The clear-air turbulence scenario consists of simulations focusing on turbulence during cloud-free conditions to understand boundary-layer growth and decay, and energy, momentum, and moisture transfers between the land and atmosphere. These are all primary processes that ultimately influence cloud formation in cloud friendly conditions. Also of relevance is the behavior of the nighttime boundary layer. Because these types of conditions occur at all ARM sites, this scenario could be executed at any of ARM's permanent sites and for many of the field campaign deployments, provided that sufficient observations are part of the campaign. The SGP location was used for discussion purposes at the workshop and the SGP would be a logical deployment location.

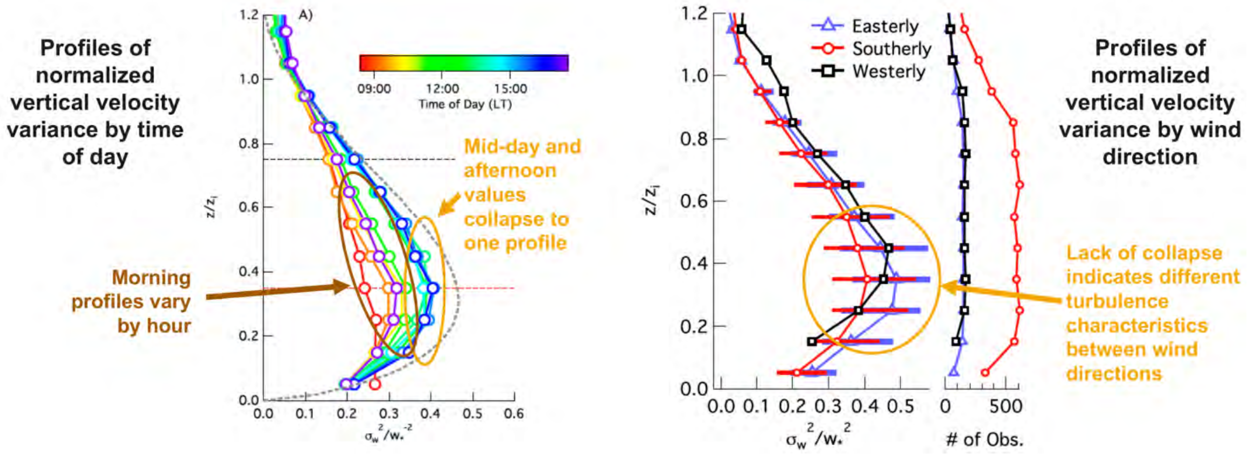

Figure 5. ARM Doppler lidar measurements at the SGP show a dependence of normalized vertical velocity variance on both time of day and wind direction, which breaks the standard scaling rules. (a) Profiles of vertical velocity (w) variance normalized by $\boldsymbol{w_*^2}$ by hour of day. (b) Similar profiles but sampled by wind quadrants with bars showing the 25th and 75th percentiles for the easterly and southerly winds. Based on Berg, Newsom, and Turner (2017). ©2017 American Meteorological Society.

The scenario proposed in the submitted white paper suggests using a modeling approach driven by choices to focus on turbulence and coupling to the surface via a homogeneous surface representative of the SGP vicinity. However, feedback from workshop participants, plus further input during the 2019 Joint ARM/ASR Principal Investigator Workshop, points toward a strong interest in including the additional science driver of the impact of surface heterogeneity on the boundary-layer behavior. This has strong implications on the model configuration, so both will be described in this section as alternative choices.

The simplest approach to configuring an LES for this scenario would be to use a domain similar to the shallow-convection scenario, but with higher resolution, a shorter model top, and reduced domain width to manage computational cost. This would entail using periodic lateral boundary conditions, grid spacing of about 25 m, a model top at 5–6 km, and a domain width of about 12 km. The surface conditions would use specified sensible and latent heat fluxes derived from ARM observations, and they would be applied uniformly across the domain. Large-scale forcings would also be applied uniformly across the domain and they would come from sources similar to the ensemble used for the shallow-convection scenario, i.e., ARM's Variational Analysis value-added product (VAP), the ECMWF IFS or ERA5, and local kilometer-scale hindcasts using the Multiscale Data Assimilation approach. An additional option is a soon-to-be-available, 36-member, ensemble data assimilation system for the High-Resolution Rapid Refresh (HRRR) model version 4 model, which is scheduled to become operational in spring 2020.

A more complicated approach would be to use a nested-LES approach where the LES-resolution grid would be nested within a coarser kilometer-scale simulation. The primary advantage of this option would be the ability to use a realistic lower-boundary treatment that includes the natural surface and vegetation heterogeneity. Scientifically, this could be important for driving intermittent turbulence in the nighttime boundary layer. Other than the boundary changes, this option would still use 25-m grid spacing and a short model top. The domain width would likely need to be larger than 12 km to capture both the spin-up fetch of the small-scale eddies on inflow boundaries plus the scales of relevant surface heterogeneity. An initial suggestion of a 25-km domain size has been made, but this would need testing to see if a narrower, more cost-efficient domain would suffice.

Simulations for either configuration option would begin with the mid-day sounding and run into the night to capture the decaying boundary layer and nighttime conditions. If deemed affordable, simulations could run beyond the following sunrise to also capture morning boundary-layer growth.

Technical modifications to the shallow-convection physics suite would be needed to accommodate the stable boundary layer. In particular, the Deardorff turbulent kinetic energy (TKE) subgrid-scale model would be replaced with an implicit LES subgrid-scale (SGS) approach using weighted essentially non-oscillatory (WENO) advection (Pressel et al. 2017). Alternatively, a more complicated dynamic subgrid-scale model could be used, but this would entail more tuning and increase computational cost (Chow et al. 2005; Zhou and Chow 2014a, 2014b).

Observations for this clear-air turbulence scenario would focus on evaluating the boundary layer, such as the thermodynamic state, turbulence characteristics, boundary-layer top, and surface fluxes (the latter if an interactive soil model is used). The lidar instruments would serve a primary role by providing profiles of thermodynamic state and turbulence characteristics. These would be combined with tower-based eddy covariance measurements. A development need would be an operational product that combines the Raman and Doppler lidar profiles to obtain profiles of moisture and temperature fluxes. Multiple researchers have done this for research-grade retrievals, but none are currently implemented as ongoing ARM products. Questions exist as to the uncertainty in such products and their ability to routinely provide useful information. Additionally, the installation of water vapor differential absorption lidars (DIALs) at the SGP extended facilities would enhance the capabilities for retrieving more accurate thermodynamic profiles at those locations. The particular type of DIAL would be a topic of discussion with instrument experts to ensure the scientific needs of the scenario would be met.

Several topics require further investigation and decisions prior to formally implementing this scenario. The most important decision is whether to use periodic boundaries with a homogeneous surface or else a nested-LES approach with an interactive soil model. This choice is driven by limitation in computational capacity combined with what level of detail is needed by the potential users. If the intermittent turbulence is strongly influenced by the regional surface variability and wave motions that encroach upon the region from far-flung influences, such as gravity waves from clouds, then the nested approach will be needed.

A related issue is how to handle the low-level jet that is common at the SGP. Jets can happen for various reasons at other locations, but their prevalence and climatic importance at the SGP makes this a somewhat unique situation. The jet can either be neglected by specifically choosing cases when the jet is not present. Or, the choice can be made to include the science driver of how the low-level jet and turbulence interact to determine the boundary-layer state. In that case, a nested domain capable of handling the physics driving the jet would be needed, which includes the gently sloping topography around the SGP (Shapiro, Fedorovich, and Rahimi 2016). Alternatively, if a periodic domain were to be used, the jet could be partially treated by forcing it into the model via the large-scale forcings. In this case, the Weather Research and Forecasting (WRF) model would need to be modified to handle time-dependent background geostrophic wind changes and tests would be needed to see how a small LES domain captures the jet influence.

An additional model question is how well the desired conditions can be simulated with implicit LES based on WENO. Tests will be needed to determine if it is adequate and if finer grid spacing than 25 m is necessary. Because of the fine resolution needed for the stable conditions, there might be a better model to use beside WRF to reduce computational cost. However, few other models have nesting capabilities.

Lastly, in addition to the desire to have additional DIAL measurement capabilities, a point raised is that investigations will be needed to determine what eddies can be measured reliably at the SGP. The most obvious issue is that the Raman lidar has a data void for the lowest approximately 500 m, which is a region of primary importance for the decaying boundary layer and during the night when near-surface fluxes drive many of the boundary-layer characteristics. There are also questions regarding what are the smallest eddies that can be observed? As the convective boundary layer decays into a stable boundary layer, smaller-scale motions begin to become more important and it is desirable to have measurements of these motions to use alongside the LES.

Overall, this scenario has received support from a number of users, particular those with an interest in surface heterogeneity impacts on turbulence. This scenario is a natural extension of the current shallow-convection scenario at the SGP and would provide a more complete picture of the boundary-layer processes occurring at the site. Instead of focusing on clouds, the scenario would focus on the underlying processes in the boundary layer that influence cloud formation.

3.5 Arctic Clouds Scenario

The arctic climate is changing faster than other regions of the planet, with warming rates nearly double those elsewhere (Screen and Simmonds 2010), leading to important implications for the cryosphere, biosphere, and human populations that live in the region. Changes to the sea ice result in feedbacks with the earth's radiation budget that further increase warming due to light-colored ice being replaced by darker sea water. Lack of physical understanding combined with inadequacies in model physics has hampered climate simulations due to climate models not being able to accurately capture the observed sea ice decline (e.g., J.C. Stroeve et al. 2012; J. Stroeve et al. 2007). Additionally, changes in arctic clouds due to the changing climate rely on parameterizations that contain uncertainties that need to be improved.

The science drivers for the arctic scenario focus around clouds and aerosol impacts on clouds. Of particular interest are mixed-phase clouds, how aerosols lead to various cloud states, and interactions of the heterogeneous surface with the boundary layer. Specific questions include:

- How is moisture distributed and moved vertically across cloud system? (The stratified arctic system)
- How does the cloud moisture budget vary over space and time? (A direct link to cloud lifetime and airmass transformation)
- What determines turbulence magnitude, mixed-layer depth, and cloud-surface coupling state?
- What role does surface heterogeneity (spatially, seasonally) play in cloud–boundary-layer structure and longevity?
- How does the cloud-top environment influence cloud processes in the Arctic?
- What is the vertical structure of radiative flux divergence profiles and how do these impact structure?
- What is the effect of free tropospheric properties on low-cloud processes?
- How do varying conditions alter mass and energy budgets of clouds, thus affecting their lifetime and/or limit cloud processes?

The location and period to be simulated would coincide with the MOSAiC field campaign that will embed an ice breaker in the arctic sea ice beginning in September 2019 and allow it to drift with the ice through October 2020. This international campaign includes participation from 17 countries and a large contribution from the ARM facility through the deployment of the AMF. MOSAiC is a unique opportunity to obtain an annual cycle of observations in an under-sampled part of the world with the potential for informing many unanswered questions about clouds and how to improve them in climate models. This once-in-a-generation, or longer, opportunity is part of the Year of Polar Prediction. Producing timely ARM simulations for MOSAiC will draw additional attention to the ARM measurements, and the heightened awareness of MOSAiC will increase the value of the LASSO scenario and ARM's campaign investments.

Figure 6. Looking toward the sea ice off of Alaska's North Slope, one can anticipate the opportunity of the MOSAiC field campaign that will embed an ice breaker into the sea ice to drift for a year through the Arctic Ocean.

The proposed model configuration for the arctic scenario must be able to handle the more stable conditions in the region plus the more stratified nature of the boundary-layer and cloud characteristics compared to the current shallow-convection scenario. Because of this, the model will need grid spacing around 20–40 m and vertical levels spaced less than 10 m within the boundary layer and cloudy layers with a stretched grid for higher levels. The fact that the boundary layer is typically shallower than 1.5 km will help offset the added cost of the vertical resolution compared to simulations at the SGP. The horizontal domain extent will be 30 km and the domain top will be around 4 km.

The simplest approach could use periodic lateral boundary conditions to enable a mature turbulent state and layered clouds to form. This would work well for cases when the ice breaker is surrounded by homogeneous sea ice or open-ocean conditions. However, a nested LES approach should also be considered for cases where the surface state is variable, particularly when the region is influenced by leads in the ice. Addressing the science drivers associated with surface heterogeneity will also require a nested approach.

Extensive surface flux measurements will be made around the ice breaker, which will enable the derivation of prescribed surface fluxes to use in the model. This was discussed during the workshop and concerns were expressed as to how to best do this to account for leads where some surface fluxes are much greater than over the frozen ice. This will be particularly important during springtime when the ocean-atmosphere temperature gradient will be strongest. One option would be to first avoid times when leads exist to focus on the simplest, yet still challenging, simulation of the arctic environment. Another option is to use an interactive sea ice model, but it is unclear if these models are of sufficient quality to ensure an accurate atmospheric simulation given the available measurements to initialize the model. The appropriate approach to use is an open issue that will need experimentation prior to implementing the arctic scenario.

The available options for large-scale forcings in the MOSAiC region are fewer than over the continental U.S. The most likely options would be to use the ERA5 reanalysis and the hourly updating Rapid Refresh (RAP) weather forecast model, which could either be converted to large-scale forcings for periodic LES domains or else used to drive a nested LES configuration. Diversity of solutions can be obtained by using a combination of the deterministic ERA5 plus the coarser ERA5 ensemble members.

The physics suite to use will be sensitive to the ice microphysics. One suggested option is to use an ensemble of microphysics parameterizations, but it is unclear if this will add more value than spending the same amount of resources on multiple large-scale forcings. At a minimum, the microphysics must be aerosol aware and be able to receive a specified aerosol profile. The LES SGS scheme will also need to be evaluated for its ability to capture the required fidelity in the arctic environment. An implicit LES SGS approach, similar to that proposed for the clear-air turbulence scenario, might be required. This will need to be evaluated against other possible options. Radiation will need to be prescribed at the model top as an upper boundary condition combined with the radiation parameterization in the model.

Aerosol profiles will need to be specified to provide sufficient information for the microphysics to operate accurately. A tethersonde will fly during portions of MOSAiC, likely in the spring, which will provide vertical profiles of basic aerosol measurements. During other times the aerosol state will need to be estimated from surface measurements or from other models. This will be somewhat problematic for ice nuclei, for which simulations are sensitive, but direct measurements will typically only be available near the surface.

An extensive list of observations to use with the arctic scenario is provided in Table 8 of the accompanying white paper (Appendix C.4). The primary focus is providing information on the state of the boundary layer and cloud characteristics. Additionally, a unique aspect of this scenario compared to other scenarios is the critical need to have surface measurements in this lightly sampled region. Critical measurements of the atmosphere include cloud condensate mass and state, cloud boundaries, and precipitation rate.

There are many uncertainties to overcome for this scenario; however, there is also great potential since MOSAiC is a rare opportunity that will provide data during the polar night and over regions rarely sampled. Implementing this scenario will require careful testing of options and a nuanced balance of ensembles to inform users of the possible range of outcomes from the model. Developing the scenario will require a number of sensitivity studies to understand the impact of the physics parameterization choices, handling of the aerosols, domain configuration, and treatment of the model's lower boundary. This scenario will also require coordination with large modeling efforts already planned for MOSAiC to avoid potential overlap and/or possibly to support LASSO with refined boundary conditions from numerical weather prediction models run for the campaign.

4.0 Common Scenario Considerations

4.1 Use of Ensembles

The use of LES ensembles for the shallow-convection scenario is a defining characteristic of LASSO. User feedback is that the availability of multiple ensemble members is valuable for their research and helps them understand the uncertainty of the simulations due to the large-scale forcings. Other users view the additional ensemble members as useful additional forcing data that provide plausible real-world conditions, which when combined with the LES, provide additional comparisons for SCM analyses. All four of the newly proposed scenarios include use of ensembles to some extent to address input and/or parameterization uncertainties. However, the cost of the new scenarios is much greater due to increased resolution and/or domain sizes, which makes the method used to determine ensemble members increasingly important. Careful consideration will be needed to balance the use of ensembles with computational need (discussed in the next section).

As detailed in the attached white papers (Appendix C), each proposed scenario includes at least some attempt to mitigate forcing uncertainty by using an ensemble of forcing information. The ERA5 and Global Ensemble Forecast System (GEFS) ensembles are available globally and can provide a range of plausible meteorological conditions for driving the LES. The ERA5 deterministic reanalysis is available with 31-km grid spacing and the related ensemble has 62-km grid spacing with 10 members, while the GEFS is archived with 1° grid spacing and has 21 members. How many LASSO realizations that could be produced from the forcings would be determined by the available computing capacity. However, for optimum use, the LASSO ensemble should contain an estimated minimum of 3–5 members. This would provide at least some model spread to more likely capture realistic conditions. The deep-convection scenario offsets much of the ensemble cost by relegating the bulk of the forcing uncertainty to an ensemble of coarser simulations with kilometer-scale grid spacing with only a few LES simulations per case. The thinking is that the coarser simulations can be used to determine which forcings perform best for the synoptic conditions, which would permit the LES to have a greater chance of initiating convection in the proper locations. A smaller "mini-ensemble" of LES would then be used to capture diversity due to small-scale convection.

Except for the clear-air scenario, where clouds are not simulated, the other three proposed scenarios also suggest the possibility of increasing the ensemble size to incorporate a variety of microphysics parameterizations or tunings. The importance of capturing this variability is unclear in relation to the forcing uncertainty. For example, the maritime scenario is focused on processes controlling precipitation; so the case-to-case sensitivity of the dependence of the precipitation on microphysics would determine whether the microphysics choice should be locked to one parametrization or treated as an ensemble member. This will need to be investigated through a series of test simulations.

Related to microphysics is the handling of aerosol profiles, which strongly impact the microphysics in the arctic and ENA regions. The arctic white paper suggests considering the use of an ensemble to cover the range of plausible aerosol states since the observations will not constrain the aerosol profile. Of particular concern is the specification of ice nuclei. However, the phase space is very large, so the white paper admits that this is not a feasible option unless a very large amount of computing power is available. Instead, a best effort will need to be made to specify the most likely aerosol profile and then leave sensitivity studies for users to perform.

In the end, the use of ensembles will realistically only be possible for the highest-priority uncertainty, which in most cases is the model forcing. The number of ensembles could vary between scenario based on the overall cost, which can differ by an order of magnitude or more between scenarios.

4.2 Computational Costs

While the intent is to not make computational cost a primary driver of the decision for which scenarios to perform for LASSO, the cost still needs to be considered. Shallow convection was the initial scenario because it could be done relatively cheaply, which aided the initial prototyping and workflow development. More expensive scenarios are being considered now that experience has been gained from the first scenario. Since test simulations have not been performed, the exact costs are unknown, so instead the costs are presented as relative to the current shallow-convection simulations. For reference, the cost of a single shallow-convection ensemble member is roughly 13,000 core hours on ARM's Cumulus cluster.

Note that the discussion of cost is strongly impacted by choices made regarding how to implement a given scenario. Changes in grid spacing have the largest impact, with roughly a magnitude cost increase for halving of the grid spacing due to an increased number of columns, decreased time step, larger output to disk, and nonlinear scaling across compute nodes. The next biggest impact is due to domain size, where a doubling of the domain width leads to roughly a four-fold increase in cost. Other choices, such as whether a doubly-periodic or nested domain is used, the number of ensemble members, cases performed per year, and simulation length are roughly linear for their cost implications, e.g., twice as many cases per year doubles the cost of the scenario. The cost of some choices is harder to quantify without testing, such as the use of different microphysics or subgrid-scale parameterizations. These types of choices are not reflected in the following discussion.

Rough estimates of the cost for each scenario are shown in Table 1. Three configurations are provided for each scenario to cover the range of possible costs depending on choices made for the particular implementation. The minimum-cost configuration ("Min" columns) reflects choosing the cheapest option for each configurable option, e.g., the coarsest grid spacing and smallest domain. As such, the minimum-cost configuration may or may not meet all the needs for the scientific drivers; however, it would meet some of them. The maximum-cost configuration ("Max" columns) uses the opposite approach and reflects choosing the most expensive choices within reasonably selected values. As can be seen for the relative cost per ensemble member, the maximum-cost options result in roughly a two-to-three-order-of-magnitude difference in cost for each configuration. Given that the minimum cost would likely not satisfy the scientific needs and the maximum cost would likely be untenable, a third option is provided that seeks a proper balance with reasonable compromises—these options are shown in the "Likely" columns. The resulting per-simulation costs relative to the operational shallow-convection simulations is 39, 23, 21, and 68 times more expensive than shallow-convection for the Arctic, clear air, deep convection, and maritime scenarios, respectively. Likewise, after factoring in reduced ensemble sizes and desired number of cases per year, the likely annual costs are 29, 31, 7.7, and 51 times, respectively. As can be seen, the use of LAM ensembles makes the deep-convection scenario very reasonably priced.

All four of the proposed scenarios would be too expensive to concurrently run on ARM's Cumulus cluster using the above likely configuration choices. The shallow-convection scenario currently uses roughly 20–25% of the cluster on an annual basis. So, additional computing power will need to be obtained. This could either be from purchasing additional compute nodes or through the DOE computer allocation request process. Given the size of these requests, the most likely request method would be via a DOE Advanced Leadership Computing Challenge (ALCC) grant. Because a scenario focused around either CACTI or ACE-ENA would be for a defined period, one could pre select case dates and estimate a priori the total computational need and thus make a more sellable ALCC request for these scenarios. In the meantime, while additional computing capacity is being obtained, an initial scenario can be implemented using the cumulus cluster by producing a smaller number of cases and using a limited ensemble size.

Table 1. Range of computation cost of each scenario relative to the current shallow-convection scenario. Note that costs due to physics differences are not included. The cost of the LAM physics ensemble for deep convection has been roughly included as half of an ensemble member.

	ShCu	Arctic			Clear-Air Turbulence			Deep Convection			Maritime		
	Operational	**Min**	**Likely**	**Max**	**Min**	**Likely**	**Max**	**Min**	**Likely**	**Max**	**Min**	**Likely**	**Max**
Individual Simulation Parameters per Ensemble Member													
Grid spacing (m)	100	50	40	20	30	25	20	150	100	100	100	50	50
Domain width (km)	25	20	30	30	10	12	15	150	150	300	25	40	60
Vertical levels (#)	226	216	247	300	225	293	333	150	200	225	250	375	400
Model top (km)	14.7	4	4	4	5	5	5	25	25	25	15	15	15
Simulation length (h)	15	24	24	36	15	18	20	8	10	24	24	30	48
Grid column count (#)	62,500	160,000	562,500	2,250,000	111,111	230,400	562,500	1,000,000	2,250,000	9,000,000	62,500	640,000	1,440,000
Grid cell count (#)	14,125,000	34,560,000	138,750,000	675,000,000	25,000,000	67,584,000	187,500,000	150,000,000	450,000,000	2,025,000,000	15,625,000	240,000,000	576,000,000
Relative time step cost	1.0	2.0	2.5	5.0	3.3	4.0	5.0	0.7	1.0	1.0	1.0	2.0	2.0
Relative cost per ens. member	1.0	7.8	39	573	5.9	23	88	3.8	21	229	1.8	68	261
Ensemble Information													
Member count (#)	8	3	3	7	4	8	8	1.5	3.5	6.5	3	3	3
Relative cost per case date	1.0	2.9	15	502	2.9	23	88	0.71	9.3	186	0.66	25	98
Annual Simulation Extrapolation													
Case dates per year (#)	30	30	60	90	30	40	50	20	25	30	30	60	90
Simulations per year (#)	240	90	180	630	120	320	400	30	88	195	90	180	270
Relative annual cost	1.0	2.9	29	1,505	2.9	31	147	0.5	7.7	186	0.7	51	294

5.0 Discussion

Discussion during the workshop occurred during the presentation of each scenario followed by an extended period at the end of the afternoon. Overall, the general consensus was that all of the scenarios are of value and would be worth implementing. Many technical details were discussed, such as how to handle boundary conditions and large-scale forcings, how to infer an aerosol profile from available observations, and the merits of different modeling approaches.

5.1 General Topics

A discussion of common elements between proposals raised several valuable points.

- The WRF model should work for each of the proposed scenarios. However, another model could be used to increase throughput for non-nested LES configurations, particularly problems requiring very small grid sizes. WRF uses more complicated and general mathematics, which leads to increased computational cost.
- Nesting was initially proposed only for the deep-convection scenario. However, discussion veered toward the value of using nested LES for other scenarios as well. For the clear-air scenario, nesting would enable looking at surface heterogeneity, while for the maritime scenario it could capture mesoscale variability. And, surface variability due to leads could potentially be captured in the Arctic. However, should nesting be used, the potential use of LASSO with SCMs will be less direct because the LES will no longer be driven by a column-based large-scale forcing, and a forcing would need to be derived for the SCM. Interpretation of the SCM-to-LES results would also change since the LES would now capture spatial heterogeneity not represented in the SCM.
- Aerosol will play a more important role in multiple scenarios. This will require a commitment to develop new aerosol profiling capabilities, whether they be direct from tethersondes and aircraft, or retrieved from ground-based instrumentation. Extrapolating surface data is not straightforward due to changes in relative humidity, aerosol loading, and composition with height.
- Scanning radars are critical for the maritime and deep-convection scenarios. Because these instruments are more difficult to maintain and use, extra attention will be needed to ensure that the data is available, of high quality, and properly integrated with the modeling results. Using past periods with known instrument and measurement characteristics is one way to deal with this issue, as for CACTI and ACE-ENA. Forward-looking LASSO scenarios will need to take this into consideration.
- Turbulence measurements are very important for the clear-air and arctic scenarios, and also important for the maritime scenario. The current shallow-convection scenario has not evaluated the turbulent characteristics of the LES or delved into incorporating these types of measurements into the LASSO skill scores. This will need to be done carefully during the prototyping stage for the new scenarios.

A discussion of the data bundle contents and how users use LASSO garnered several important points. The first is that the ability to reproduce cases via the range of forcings is very valuable for researchers. Including the forcing data alongside the LES is a popular aspect of the LASSO data bundles. The second is that there is a desire to download specific variables across a large number of simulations. This capability will become more important as the number and types of LASSO cases increases. Presently, this is not possible since users must download entire model output files for entire simulations.

5.2 Measures of Success

Measures of success were also discussed. The traditional metrics of user count and number of citations were suggested. Additionally, engagement with external groups was noted as valuable. For example, LASSO being used in non-ARM projects, being included in workshops and meetings, and links to large-scale modeling groups. It was noted that the Global Energy and Water Exchanges Project (GEWEX) land-atmosphere community would be potentially interested in the clear-air scenario if it were to include surface heterogeneity. Having LASSO cases used for model intercomparison studies, such as through the Global Atmospheric System Studies Panel (GASS), would also raise visibility and garner greater usage of the data. For use by large-scale model developers, connections to the E3SM development team have been sought, and related collaborations will continue to be developed. Just recently, it has been announced that LASSO forcing data is now include in v3 of NOAA's Global Model Testbed Single-Column Model.

5.3 Implementation Timing Considerations

Each scenario has different constraints regarding data availability and model development and diagnostics/skill score work that must be done during a prototyping stage prior to beginning operations. Additionally, some scenarios require development of new observational products that will take time. Because of these constraints, thought must go into when work could begin on each scenario and how long it would be until a viable set of data bundles could be produced.

The clear-air scenario would be the most likely to have sufficient information to begin prototyping as soon as funding and staffing are available. Historical cases from the past several years, essentially since the extended facilities with Doppler lidars and AERIs became viable in 2016, could be used for development purposes. A period of time would be needed to test different model configurations, such as determining which grid spacing and subgrid-scale method to use for the stable conditions, and whether a model faster than WRF is needed. It would also be desirable to compare nested versus periodic domain configurations given the community interest in capturing the surface heterogeneity. The biggest unknown, in terms of timing, would be development of an operational set of retrievals for the flux profiles for heat and moisture.

Timing for the deep-convection scenario is predominately determined by the availability of quality-controlled data now that the CACTI field campaign has ended. Current estimates are that radar data will be available in a form for initial research use around January 2020. In the meantime, one could begin developing the LAM ensemble approach and start testing model configurations for the LES.

Implementation of the full data bundle would require waiting until all the available data is quality controlled.

The ACE-ENA field campaign has also ended and the resulting observations are beginning to become available. The bigger issues impacting the maritime scenario timing are the handling of the LES lower boundary, availability of spatial estimates of precipitation, and aerosol profiles. Investigation is needed regarding the available buoy measurements and modeling comparisons to determine whether the sea surface temperature or surface fluxes should be specified for the LES lower boundary. The best data source for either of these options is an open question. The needed gridded precipitation retrievals are under development and should be available soon after suitable peer review. However, they are new and require time for understanding their nuances. Handling of the aerosol profile will require developing a new retrieval that extrapolates surface aerosol measurements aloft through a combination of sounding and lidar measurements. Alternatively, cases could be chosen based on the availability of aircraft data.

The arctic scenario has the longest outlook given that the MOSAiC field campaign does not end until October 2020. Data quality and evaluation will likely take about an additional year, although some data will become available earlier as hard drives are returned during resupply trips. Some level of vetting should be done of the data before LASSO attempts to use them. Further, LASSO might need data from other groups, for which permission may be obtained, but may delay LASSO releases until the embargo period has lapsed. Other aspects of the arctic scenario could also benefit from waiting as details from other scenarios are worked through. For example, the methodology used to determine aerosol profiles at ENA might be useful for MOSAiC too. The work to evaluate how to best simulate the stable boundary layer for the clear-air scenario could inform how to configure the LES for the Arctic. Delaying, however, potentially could lose the window of opportunity of when LASSO could have the biggest impact.

All four scenarios will require domain configuration testing, development of metrics, and evaluation of how well the model simulates the desired conditions. This will require a fair amount of time to do at scale given the more expensive domains anticipated for these scenarios. Finally, it is worth noting that an iterative learning curve occurs as successive sets of LASSO cases are generated and released. Since LASSO is a “super VAP,” requiring inputs from multiple VAPs, a suitable gestation period is needed to focus on one scenario before moving to the next.

6.0 Conclusions

Much has been learned about how to incorporate modeling into ARM since the LASSO pilot project started in 2015. The time taken to develop the data bundle concept has helped highlight relevant data sets that modelers can use as well as served as a unifying force to improve different aspects of the measurements and subsequent VAPs. The value is not just in the modeling, but also in the improvements to the ARM facility as a whole. For example, the AERIoe VAP has been a particular focus of attention as it potentially can provide a wealth of information about both liquid water paths and thermodynamic profiles in the lower troposphere. LASSO has been one of the primary initial uses of this new product that draws from both the AERI and 3-channel MWR instruments

(MWR3C). This need has driven improvements to the AERIoe algorithm and served as a continued push for improving calibration of the MWR3C. The improvements at the SGP benefit many users beyond LASSO and will also propagate to other ARM locations where LASSO is not yet implemented.

By expanding LASSO into new scenarios, ARM will increase the unifying attention of LASSO from shallow convection to many more aspects of ARM's measurements. For example, scanning radar data is relatively new within ARM's capabilities and many users do not have a good understanding of what is possible with these data due to a combination of lack of expertise and the difficulty of working with these large data sets on cumbersome radial grids. Including this type of data in a deep-convective LASSO scenario will open new possibilities by demonstrating the data set's use. Likewise, the Doppler lidar ability to retrieve vertical velocity variances is another relatively new capability that would be highlighted within the clear-air or maritime scenarios. The symbiotic nature of LASSO is a clear outcome of the LASSO efforts to date.

Over the next several years, it is anticipated that multiple new LASSO scenarios will be implemented and that all four of the proposed scenarios discussed in the LASSO Expansion Workshop could be implemented within the coming decade. As these new scenarios become available, it would be good for ARM to continue to be open to new possible scenarios, particularly within the context of significant new field campaigns and mobile facility deployments. LASSO can serve to quicken the scientific learning from these deployments by drawing attention to the data and maintaining a continued focus on the related observations for multiple years beyond what would typically be the primary focus.

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Zhou, BW, and FK Chow. 2014a. "Nested large-eddy simulations of the intermittently turbulent stable atmospheric boundary layer over real terrain." *Journal of the Atmospheric Sciences* 71(3): 1021–1039, https://doi.org/10.1175/Jas-D-13-0168.1

Zhou, BW, and FK Chow. 2014b. "Nighttime turbulent events in a steep valley: A nested large-eddy simulation study (vol 70, pg 3262, 2013)." *Journal of the Atmospheric Sciences* 71(6): 2280–2280, https://doi.org/10.1175/Jas-D-14-0036.1

Appendix A:

LASSO Background Information

A.1 LASSO Background Material

Detailed descriptions of LASSO can be found in the following web pages and reports.

A.1.1 LASSO-Related Websites

LASSO website:	https://www.arm.gov/capabilities/modeling/lasso
LASSO Bundle Browser:	https://archive.arm.gov/lassobrowser
LASSO listserv archive:	https://us11.campaign-archive.com/home/?u=74cd5b8a5435b8eca383fc18c&id=38f02e1568
Expansion blog series:	https://www.arm.gov/news-events/search?news-category[0][0]=post&news-category[1][0]=LASSO
Call for expansion white papers:	https://www.arm.gov/news/facility/post/52808
ARM Communications posts for LASSO:	https://www.arm.gov/news-events/search?q=LASSO&news-category[0][0]=post

A.1.2 LASSO Technical Reports

Gustafson, WI, and AM Vogelmann. 2015. LES ARM Symbiotic Simulation and Observation (LASSO) Implementation Strategy. U.S. Department of Energy. DOE/SC-ARM-15-039, https://www.arm.gov/publications/programdocs/doe-sc-arm-15-039.pdf

Gustafson, WI, AM Vogelmann, X Cheng, S Endo, B Krishna, Z Li, T Toto, and H Xiao. 2016. Description of the LASSO Alpha 1 Release. U.S. Department of Energy. DOE/SC-ARM-TR-194, https://doi.org/10.2172/1373564

Gustafson, WI, AM Vogelmann, X Cheng, S Endo, B Krishna, Z Li, T Toto, and H Xiao. 2017. Description of the LASSO Alpha 2 Release. U.S. Department of Energy. DOE/SC-ARM-TR-199, https://doi.org/10.2172/1376727

Gustafson, WI, AM Vogelmann, X Cheng, S Endo, B Krishna, Z Li, T Toto, and H Xiao. 2017. Recommendations for the Implementation of the LASSO Workflow. U.S. Department of Energy. DOE/SC-ARM-17-031, https://doi.org/10.2172/1406259

Gustafson, WI, AM Vogelmann, X Cheng, S Endo, KL Johnson, B Krishna, Z Li, T Toto, and H Xiao. 2018. Description of the LASSO Data Bundles Product. U.S. Department of Energy. DOE/SC-ARM-TR-216, https://doi.org/10.2172/1469590

A.2 Shallow-Convection Scenario Technical Details

The following tables summarize relevant technical details of the shallow-convection scenario. This information is taken from Description of the LASSO Data Bundles Product (Gustafson et al. 2018).

Table 2. Summary of key configuration choices for the shallow-convection scenario.

Detail / Parameter	Setting / Value
Model	Modified version of Weather Research and Forecasting (WRF) (Skamarock et al. 2008; Endo et al. 2015)
Grid spacing	100 m
Domain width	25 km
Number of levels	226
Vertical grid spacing	30 m up to 5 km; stretches to 300 m at model top
Domain top	14.7 km
Simulation start time and length	12 UTC; integrated for 15 h
Initial conditions	Horizontally homogeneous profile from 12 UTC sounding plus random temperature perturbations in lowest level
Lateral boundary conditions	Doubly periodic
Surface boundary conditions	Spatially homogeneous surface fluxes from ARM observations in VARANAL
Subgrid-scale scheme	1.5 order turbulent kinetic energy (Deardorff 1980)
Microphysics parameterization	Thompson (Thompson et al. 2008; Thompson, Rasmussen, and Manning 2004)
Radiation parameterization	Rapid Radiative Transfer Model for Global Climate Models (RRTMG) (Clough et al. 2005; Iacono et al. 2008; Mlawer et al. 1997)

Table 3. Summary of large-scale forcings used to construct the LASSO eight-member LES ensembles.

Large-Scale Forcing Source	Scale(s) of Extracted Forcings
Variational Analysis (VARANAL)	300 km
ECMWF Integrated Forecast System	9, 114, & 413 km
Multiscale Data Assimilation (MSDA)	75, 150, & 300 km
No Large-Scale Forcing	N/A

Table 4. Observations provided with the LASSO shallow-convection data bundles.

Instrument/Value-Added Product	Variable Measured or Retrieved
AERIoe, MWRRet	In-cloud liquid water path
Active Remote Sensing of Clouds (ARSCL)	Boundary-layer cloud fraction and time-height cloud mask
Total sky imager (TSI)	Opaque cloud fraction
MET and Mesonet stations within 60 km	Surface temperature and moisture conditions plus regional lifting condensation level
Radiosonde	Thermodynamic profiles, typically 4 times per day
Raman lidar	Mid-boundary-layer temperature and moisture
Doppler lidars at Central and boundary facilities	Boundary-layer cloud-base height

A.3 Articles Citing LASSO

The following list includes articles citing or mentioning LASSO as of April 10, 2019. Note that articles in black used LASSO data as part of their analysis, and articles in gray cite LASSO without using any data.

Angevine, WM, J Olson, J Kenyon, WI Gustafson, S Endo, K Suselj, and DD Turner. 2018. “Shallow cumulus in WRF parameterizations evaluated against LASSO large-eddy simulations.” *Monthly Weather Review* 146(12): 4303–4322, https://doi.org/10.1175/mwr-d-18-0115.1

Emeis, S, N Kalthoff, B Adler, E Pardyjak, A Paci, and W Junkermann. 2018. “High-resolution observations of transport and exchange processes in mountainous terrain.” *Atmosphere* 9(12): 457, https://doi.org/10.3390/atmos9120457

Fast, JD, LK Berg, L Alexander, D Bell, E D'Ambro, J Hubbe, C Kuang, J Liu, C Long, A Matthews, F Mei, R Newsom, M Pekour, T Pinterich, B Schmid, S Schobesberger, J Shilling, J Smith, S Springston, K Suski, JA Thornton, J Tomlinson, J Wang, H Xiao, and A Zelenyuk. "Overview of the HI-SCALE field campaign: A new perspective on shallow convective clouds." *Bulletin of the American Meteorological Society*: 100(5): 821–840, https://doi.org/10.1175/bams-d-18-0030.1

Feingold, G, A McComiskey, T Yamaguchi, JS Johnson, KS Carslaw, and KS Schmidt. 2016. "New approaches to quantifying aerosol influence on the cloud radiative effect." *Proceedings of the National Academy of Sciences* 113(21): 5812–5819, https://doi.org/10.1073/pnas.1514035112

Fitch, AC. 2019. "An improved double-gaussian closure for the subgrid vertical velocity probability distribution function." *Journal of the Atmospheric Sciences* 76(1): 285–304, https://doi.org/10.1175/jas-d-18-0149.1

Ghate, VP, P Kollias, S Crewell, AM Fridlind, T Heus, U Loehnert, M Maahn, GM McFarquhar, D Moisseev, M Oue, M Wendisch, and C Williams. 2019. "The second ARM training and science application event training the next generation of atmospheric scientists." *Bulletin of the American Meteorological Society* 100(1): ES5–ES9, https://doi.org/10.1175/Bams-D-18-0242.1

Griewank, PJ, V Schemann, and RAJ Neggers. 2018. "Evaluating and improving a PDF cloud scheme using high-resolution super large domain simulations." *Journal of Advances in Modeling Earth Systems* 10(9): 2245–2268, https://doi.org/10.1029/2018ms001421

Mechem, DB, and SE Giangrande. 2018. "The challenge of identifying controls on cloud properties and precipitation onset for cumulus congestus sampled during MC3E." *Journal of Geophysical Research: Atmospheres* 123(6): 3126–3144, https://doi.org/10.1002/2017jd027457

Neggers, RAJ, PJ Griewank, and T Heus. 2019. "Powerlaw scaling in the internal variability of cumulus cloud size distributions due to subsampling and spatial organization." *Journal of the Atmospheric Sciences*: in press, https://doi.org/10.1175/jas-d-18-0194.1

Oue, M, P Kollias, KW North, A Tatarevic, S Endo, AM Vogelmann, and WI Gustafson. 2016. "Estimation of cloud fraction profile in shallow convection using a scanning cloud radar." *Geophysical Research Letters* 43(20): 10,998–11,006, https://doi.org/10.1002/2016GL070776

van Laar, TW, V Schemann, and RAJ Neggers. 2019. "Investigating the diurnal evolution of the cloud size distribution of continental cumulus convection using multiday LES." *Journal of the Atmospheric Sciences* 76(3): 729–747, https://doi.org/10.1175/jas-d-18-0084.1

Wulfmeyer, V, DD Turner, B Baker, R Banta, A Behrendt, T Bonin, WA Brewer, M Buban, A Choukulkar, E Dumas, RM Hardesty, T Heus, J Ingwersen, D Lange, TR Lee, S Metzendorf, SK Muppa, T Meyers, R Newsom, M Osman, S Raasch, J Santanello, C Senff, F Späth, T Wagner, and T Weckwerth. 2018. "A new research approach for observing and characterizing land-atmosphere feedback." *Bulletin of the American Meteorological Society* 99(8): 1639–1667, https://doi.org/10.1175/bams-d-17-0009.1

A.4 Download Statistics for LASSO

Download statistics of the LASSO data bundles during the period October 2017 through September 2018 for the 2017 and 2018 data bundles are summarized in Table 5. This period is during the transition from the pilot phase to operational phase of LASSO and therefore represents a sampling of the preliminary and early adopters of LASSO. In total, 40 users were logged downloading one or more data bundles with 16 of those users downloading at least five bundles. We consider these the more serious users who are likely using LASSO for research since the threshold excludes users downloading only a couple of bundles to examine what they contain. However, it is possible that some users only needed one or two bundles to do their investigations.

Table 5. Download statistics for the period October 2017 through September 2018 for the 2017 and 2018 data bundles.

Category	Usage
Number of unique users	40
Minimum and maximum number of data bundles downloaded by a user	1, 160
Mean number of data bundles downloaded per user ± 1 standard deviation	25.9 ± 40.5
Number of users downloading ≥ 5 data bundles	16

A.5 Timeline of the LASSO Expansion Process

The following timeline highlights important steps taken to reach out to the community of potential LASSO users to seek guidance on priorities, expectations, and potential modeling approaches that would fulfill ARM's intentions for LASSO. Effort was made to specifically target a wide variety of users from within the DOE and university atmospheric science communities as well as researchers both within the United States and internationally. Multiple attempts were made to receive user feedback including in-face sessions at meetings, presentations, and online marketing.

July 2017	Presented a poster at the Future of Cumulus Parametrization, Delft, Netherlands, to reach out to potential international users and beyond the typical DOE audience.
September 2017	Presentation to the ARM User Executive Committee on the status of ARM that provided a general overview of the expansion process.
December 2017	Convened a town hall meeting at the 2017 American Geophysical Union Fall Meeting, New Orleans, Louisiana, as the first public outreach effort for the LASSO expansion effort. Poster presentations were also given.

February 2018	Submitted a letter to Sally McFarlane, DOE ARM Program Manager, as part of the response to the ARM Triennial Review; the letter outlined the planned expansion process.
March 2018	Presented a talk and poster at the Understanding and Modelling Atmospheric Processes, 2nd Pan-GASS Meeting, Lorne, Australia, to reach out to potential international users and beyond the typical DOE audience.
March 2018	Held a breakout session and presented a poster on LASSO at the 2018 ARM/ASR Principal Investigator Meeting, Vienna, Virginia, targeting scientists within the DOE ASR research community; the breakout included an hour devoted to a guided discussion on potential expansion scenarios with notes from the time available at https://asr.science.energy.gov/meetings/stm/2018/presentations/626.pdf
August 2018	Presented a talk at the 2018 ARM Developers' Workshop, Argonne, Illinois, targeting the ARM software development and infrastructure teams to make them aware of the LASSO growth possibilities.
August 2018	Poster presentation at the American Meteorological Society 15th Conference on Cloud Physics, Vancouver, British Columbia, targeting the academic research community.
November 2018	Poster presentation at the 2018 DOE Modeling Principal Investigator Meeting, North Potomac, Maryland, targeting the E3SM research and development community.
December 2018	Poster presentation at the 2018 American Geophysical Union Fall Meeting, Washington, D.C., targeting the general atmospheric science community.
June–December 2018	Produced a five-part blog series on the ARM website, https://www.arm.gov/news-events/search?news-category[0][0]=post&news-category[1][0]=LASSO, that outlined the four most likely expansion scenarios; each entry also had an accompanying email to the LASSO email distribution list, https://us11.campaign-archive.com/home/?u=74cd5b8a5435b8eca383fc18c&id=38f02e1568, and an interactive forum for users to post their thoughts, https://github.com/ARM-DOE/lasso-public/issues

January 2019	Issued an open call for white papers from the community for users to suggest LASSO scenarios with accompanying high-priority science drivers and modeling strategies, https://www.arm.gov/news/facility/post/52808; white papers were due March 8, 2019. As feedback from the LASSO breakout session from the 2018 ARM/ASR PI meeting indicated strong interest in scenarios for arctic clouds, deep convection, and maritime clouds, three teams were recruited to write papers on these scenarios to ensure a coordinated, group consensus on these high-priority options.
May 2019	Held the LASSO Expansion Workshop, Boulder, Colorado, to discuss the white paper submissions, prioritization of science drivers, and feasibility of different modeling approaches, and to work out details of the proposed modeling strategies.
June 2019	Held a breakout and presented a poster on LASSO at the 2019 Joint ARM/ASR Principal Investigator Meeting, Bethesda, Maryland, to present findings from the LASSO Expansion Workshop and to provide a final open forum for community input prior to submitting this report to ARM management.
August 2019	Finalized this report and submitted it to ARM management.
Late 2019	ARM management decides on the next phase(s) of LASSO.

Appendix B:

LASSO Expansion Workshop Details

The LASSO Expansion Workshop was held May 2, 2019 at the Foothills Laboratory of the National Center for Atmospheric Research in Boulder, Colorado. The purpose of the workshop was to review future LASSO scenarios that had been proposed via a white paper process that resulted in four white papers.

Figure 7. Group photo of attendees at the LASSO Expansion Workshop.

B.1 Workshop Agenda

Background Information

8:15 a.m.	Welcome, logistics, and overview of the meeting
8:30	Current LASSO implementation: user base, status, lessons learned
8:45	The expansion decision: drivers, process, scope, timeline, initial questions

Presentation of Proposed Scenarios

Each scenario has a 20-min. presentation with the remainder of the time block devoted to clarifying questions and addressing related open issues.

9:00	Maritime clouds/East North Atlantic location
10:00	*Morning break*
10:15	Deep convection/Southern Great Plains or alternative location

11:15 Clear-air turbulence/Southern Great Plains or alternative location

12:00 p.m. Lunch

1:30 Arctic clouds/North Slope of Alaska or MOSAiC location(s)

Discussion

2:30 Overall feedback, identification of core LASSO components

3:30 Afternoon break

4:00 Readdressing and refinement of science goals, measures of success, and ensuring we captured everything

White Paper Enhancements

5:00 Groups meet to address modification to their white papers based on information from the meeting

5:45 p.m. Adjourn formal meeting

Appendix C:

Submitted LASSO Expansion White Papers

The following four white papers were submitted to the LASSO Expansion Workshop and reflect minor modifications submitted by the writing teams based on discussion at the workshop.

C.1 Maritime Clouds Scenario White Paper

LASSO Expansion Scenario

Routine Large-Eddy Simulations of Marine Boundary-Layer Clouds over the Eastern North Atlantic

A White Paper Submitted to the
Atmospheric Radiation Measurement user facility

Writing Team: Robert Wood, Richard Forbes, Graham Feingold, and Pavlos Kollias

C.1.1 Short Description

- Large-eddy simulations (LES) of marine low clouds under a wide array of meteorological forcings will be conducted and compared with the suite of remote-sensing and in situ data at the ARM Eastern North Atlantic (ENA) site on Graciosa Island in the Azores.
- Major focus on understanding and simulating precipitation processes in marine stratocumulus cases in well-mixed and decoupled (cumulus coupled) boundary layers.

C.1.2 Science Drivers

- Low-cloud feedbacks, and particularly those involving marine low clouds in subsiding environments, are the largest source of diversity in projections of how the earth will warm in the 21st century.
- Marine low clouds in climate models are highly sensitive to increases in anthropogenic aerosol loading and a large fraction of the global aerosol indirect forcing is realized over portions of the oceans dominated by low clouds.
- Climate models have been shown to poorly represent precipitation formation in low clouds in general. Studies suggest that large-scale models overestimate the frequency of light precipitation and likely underestimate its strength. Both observations and process modeling support the idea that increased aerosol loading may result in a suppression of light precipitation, but it is unclear how accurately climate models represent this suppression of precipitation.
- Climate models almost universally produce increases in cloud condensate and/or cloud cover in response to aerosol-suppressed precipitation. This result appears to be inconsistent with high-resolution cloud-resolving models, which show that cloud responses to precipitation suppression are sensitive to the meteorological state. There is a scale mismatch between the climate model results, which are typically averaged over long periods, and cloud-resolving

simulations, which are small in number and are not necessarily reflective of all meteorological conditions. Although there is an emerging consensus that climate models may incorrectly represent macrophysical cloud adjustments to aerosol, it is unclear how strong these responses are across a wide variety of meteorological regimes.

- A large suite of cloud-resolving simulations spanning a wide range of different meteorological conditions, when taken together with detailed observations from the ENA site, and single-column versions of large-scale models, will (a) test the ability of both cloud-resolving and large-scale models to correctly represent precipitation formation processes; (b) be used to establish the range of conditions under which aerosols suppress precipitation; and (c) serve as benchmarks for the comparison of cloud-resolving and climate models.

C.1.3 Full Description

The Azores experiences a range of cloud regimes that is broadly representative of the global oceans as a whole. This presents an opportunity for low-cloud modeling in that an array of different boundary-layer and cloud structures can be simulated at a single site. The ENA observatory instrument suite is now essentially complete including the two-phase Aerosol-Cloud-Experiments (ACE-ENA) that provided a wealth of in situ observations to evaluate the remote-sensing algorithms. In addition to standard sensors found at all ARM observatories, the ENA site includes (a) the latest (2nd) generation ARM radars (KAZR2, SACR2, XSAPR2) providing radar characterization of cloud and precipitation vertical and horizontal structure at three frequencies (W, Ka, and X-band), providing the first island-based documentation of the 4D evolution of low-level clouds and precipitation; (b) a Raman lidar that provides vertical temperature, humidity, cloud/aerosol feature detection, and aerosol extinction, and a Doppler lidar that provides both vertical turbulent wind profiles as well as horizontal wind profiling.

Precipitation from low clouds has been shown to be important for determining aerosol sensitivity in models, and for initiating cloud field transitions such as the stratocumulus-to-cumulus transition. Approximately 80% of the low clouds at the ENA site generate detectable precipitation falling below their bases, and it is critical to understand (a) the relationship between the frequency and rate of precipitation and the cloud and cloud-controlling meteorological factors; (b) the relationship between precipitation and mesoscale variability in the cloud fields; and (c) the sensitivity of precipitation to changes in aerosol loading.

A suite of observational products is either currently available or will be available soon to provide quantitative precipitation estimates that can be used to constrain models. The list of observational products includes: sub-cloud-layer drizzle microphysical retrievals, turbulence retrievals in the sub-cloud and cloud layer and quality-controlled, gridded radar reflectivity and rainfall rates from the scanning radars.

We envision a LASSO effort applied to the ENA site that would aim to sample a range of different cases in a routine manner. On many days of the year, the Azores experiences low cloud fields that would be conducive to LES modeling. Of course, on many of the days the cloud fields may not be ideal, but we think that LASSO's strength is in being able to simulate clouds in a routine manner that will then allow us to compare with observations under a wide range of conditions to evaluate under which conditions the LES is most faithfully able to capture the key features of the PBL and cloud fields. Computational resource limitations mean that not all days will be chosen for simulation by LASSO, so a combination of ENA site observations and an existing meteorological regime classification (e.g., self-organizing maps) can be used together to identify a set of cases that best represents the diversity of different cloud and meteorological conditions at the ENA site.

A key focus for the analysis of LASSO model output is to help elucidate the physical processes that generate precipitation in shallow marine clouds. Exploring the sensitivity of simulations to choices of treatment of collision-coalescence (autoconversion, accretion, self-collection), raindrop sedimentation, and the role of turbulent recirculation of drizzle drops, would all be worthwhile components of a LASSO effort. There is an open question regarding the extent to which we will simulate aerosol sources (e.g., surface versus free troposphere, advection) and sinks (e.g., coalescence scavenging) during the cloud life cycle/simulation. Precipitation removal of cloud droplets has been shown to be important on relatively short timescales in the stratocumulus-to-cumulus transition in other regions.

Focal science questions to address include:

- How do even relatively thin clouds at the ENA site produce detectable precipitation?
- Is low-cloud precipitation at the ENA site controlled primarily by the availability of condensate, and how sensitive is it to cloud droplet concentration?
- How do meteorological controls, such as wind speed and turbulent mixing in the PBL, affect condensate and precipitation?
- How strongly are cloud droplet sizes and concentrations related to aerosol properties measured at the surface and what cloud processes are important for controlling the relationship?

C.1.4 Model Configuration

Domain and resolution: The ideal LES domain will be centered over the ENA site on Graciosa Island with a domain size that is sufficiently extensive to capture key mesoscale structures that are associated with closed and open cell convection and are also sampled with the scanning X-band radar (X-SAPR2). A domain size of ~20–60 km is likely to be adequate for resolving at least some of the mesoscale variability, although flexibility to experiment with the domain size will be required to establish if this can be reduced in some cases. It is important to stress that high vertical and horizontal resolution is also required to accurately represent key processes such as cloud-top entrainment. Table 6 presents a suggested configuration for LASSO at the ENA site that balances the needs for both high resolution and a domain size that can capture mesoscale variations.

Table 6. Suggested configuration for LASSO routine LES simulations over the ENA site.

Category	Suggested configuration
Horizontal resolution and domain	~50–100 m resolution with a domain 20–40 km across. Periodic boundary conditions.
Vertical resolution and domain	10–20 m in the PBL, stretching to several hundred meters well above low-cloud tops.
Model physics	Bulk aerosol-aware microphysics that includes an aerosol activation scheme so that the model can be forced with observed CCN/aerosol properties measured at the ENA site.

Island effects: We do not recommend attempting to reproduce the island effects of Graciosa in the simulations. The ENA site was chosen specifically to minimize island impacts, and most of the time this has been successful: the site is within a km of the ocean for most common wind directions (W through to NE) that produce low cloud fields. Island effects on clouds are occasionally evident during periods of southerly or southeasterly flow, and during periods of very light winds.

Computational costs: The current version of LASSO running at the Southern Great Plains ARM site uses a horizontal resolution of 100 m within a 24.-km-wide domain. Such a configuration is on the low side of our proposed domain size range and is on the coarse end of our recommended grid spacing (Table 6). Cloud-top entrainment into marine stratiform clouds tends to require a relatively small horizontal spacing closer to 50 m. If the LES domain for LASSO at ENA is kept the same as that used at SGP, the doubled resolution would increase cost over the current LASSO simulations by roughly a factor of 8. Another issue is vertical grid spacing. Currently, LASSO uses 226 levels with dz≅30 m up to 5 km and then is stretched up to a spacing of 300 m at the model top at 14.7 km. For ENA, where cloud-top entrainment is important, we suggest a vertical grid spacing between 10–20 m, so we could roughly assume doubling the number of levels over the current LASSO. This would then roughly double the cost assuming the timestep requirements would be handled in the 8x factoring for the horizontal grid changes. Combining horizontal and vertical resolution requirements suggests a cost increase of 16 times the current cost. This assumes no changes to the domain size, which may add another factor of 4–8 to the simulation costs should a 60-km domain prove necessary.

C.1.5 Input Data such as Initial, Forcing, and Boundary Conditions

Large-scale forcing and boundary conditions: Due to the absence of a sounding network surrounding ENA that could be used to produce a forcing analysis, we instead must rely on meteorological analyses/reanalyses to provide large-scale dynamic and thermodynamic forcing to drive the LES simulations. ENA soundings are incorporated into meteorological analyses via the GTS. Investigators have successfully used such forcing to produce realistic simulations of clouds at the ENA site (Rémillard et al. 2017; David Mechem, personal communication), and others are exploring the use of a nested approach using WRF to simulate a large outer domain that then is used to drive a cloud-resolving nested inner grid.

An issue at the ENA site is that surface flux measurements are impacted by the island itself even when there is insufficient time for these impacts to affect the clouds aloft. Thus, it is recommended that the turbulent moisture and sensible heat fluxes measured at the site are not used to drive the simulations. There have been some sporadic meteorological measurements at a nearby buoy that could be used to calculate surface fluxes using a bulk formulation, but the quality of such measurements has not been adequately assessed. An evaluation of the surface fluxes from the ECMWF IFS over ocean for the Marine ARM GPCI Investigations of Clouds (MAGIC) campaign showed that they were in generally good agreement with the ship-derived bulk fluxes.

Ensemble simulations: The lack of a sounding network at the ENA site means that there are limited large-scale forcing options available to drive LES at ENA. However, one could still explore the sensitivity to different forcing scales and to different physics configurations in the LES. For LASSO at SGP, forcing data from different models/reanalysis and three different averaging resolutions from the ECWMF IFS were used, in addition to the direct observation forcings. Although the three different model averaging scales may have a smaller impact than switching between different model/reanalysis systems, it would be possible to use different averaging resolutions at ENA to create a forcing ensemble. Using reanalysis gives a consistent data set for forcing over time, e.g., ERA5 is now available with data every hour. Adjusting different parametrizations, e.g., microphysical schemes, in the model is also a possibility for creating an ensemble of simulations. This may be important if the key cloud/precipitation-controlling processes at the ENA site are particularly sensitive to different schemes.

There is thus the potential for the use of LES ensembles to be used at ENA to explore simulation sensitivity to meteorological forcings and to the representation of physical processes. These may be useful for final case selection and to understand which physical processes are contributing most strongly to simulation diversity.

Aerosol boundary conditions: Surface CCN spectra and the accumulation mode aerosol size distribution are continually measured at the ENA site. Together, these would be used to provide estimates of the aerosol hygroscopicity (kappa) that is then used to provide composition information required by the activation scheme within the LES (e.g., Abdul-Razzak and Ghan). Additional composition information is provided by an aerosol chemical speciation monitor (ACSM) that operates at the ENA site and provides a breakdown of the composition using a bulk mass spectrometry approach.

C.1.6 Evaluation Data and Approach

The proposed focus of LASSO-ENA on precipitation processes in shallow clouds and their controlling factors lends itself well to the unprecedented radar and lidar instruments at the site. Table 7 provides a listing of the currently-available main sources of evaluation data that will be used to compare against the LES simulations.

We also see opportunities for expanding the observational capabilities at the ENA site specifically with a view to improving our ability to test the LES simulations. The following section describes some of the potential improvements that might be most useful for the LASSO effort.

Table 7. Primary evaluation data and required instruments for an ENA scenario.

Evaluation dataset	Instruments
Precipitation estimates at the surface, below cloud, and in-cloud	KAZR2/Ceilometer, KASACR2, X-SAPR2, Parsivel disdrometer
Cloud condensate (vertically integrated and profiling)	MWR LWP; KA/W-SACR Dual-Wavelength Ratio (DWR) technique; AERI/MWR for low LWP conditions
PBL turbulence	Doppler Lidar (subcloud); KAZR Doppler velocity (in-cloud)
Cloud and aerosol layers	ARSCL (cloud); Raman lidar (aerosol)
Cloud radiative/microphysical properties (optical thickness and droplet effective radius)	Downwelling SW radiation/narrow field of view radiometer/MWR estimates of cloud optical thickness

Additional observations

Buoy for meteorological and flux measurements: as discussed in Section C.1.5, the surface fluxes measured at the ENA site are not reliable estimates of those over the open ocean around Graciosa. If reliable meteorological measurements (winds, temperature, and pressure) can be installed on one of the buoys surrounding Graciosa (buoys primarily installed for earthquake/tsunami warnings), this would permit the use of bulk fluxes for initializing the LES.

Tri-Doppler lidar network: Contrary to tri-Doppler radar system, a tri-Doppler lidar network can be established in a small area around the ENA observatory. One of the systems can be the existing Doppler lidar at the ENA and two additional systems can be developed within 250 m to a 1 km spacing from the ENA observatory (Klein et al. 2015). The tri-Doppler lidar system can provide high-spatial-resolution ultraviolet (UV) measurements that can cover the boundary-layer (BL) scales and allow us to study the interaction of two-dimensional (2D)/3D flows from the surface to the cloud base. Furthermore, we can use “virtual” towers and estimate U,V,W at very high temporal resolution. In addition, we can use the network of Doppler lidars to document cloud fraction using a larger sampling volume, thus improving the representativeness of our measurements to domain-average properties.

Stereo-camera network: A set of three stereo cameras spaces by 2–3 km to provide 4D gridded view of shallow clouds (Romps et al. 2018). One of the cameras will be at the ENA observatory and the other two will be installed at a distance of 2–3 km from each side of the ENA observatory. The cameras will look in a north direction and provide stereoscopic views of shallow clouds.

Meteorological particle spectrometer: (MPS; Baumgardner et al. 2002): The MPS uses a linear array of 64 photodiodes to measure the shadow images of particles falling through a collimated laser beam. The MPS instrument has 50-µm resolution and is suitable for measuring small drops. The size range is from 50 µm to 3.1 mm, and its sampling area is 6.2 cm^2. This instrument, next to the Parsivel and 2DVD disdrometer, will provide drizzle size distributions.

Opportunities for testing single-column models

The LASSO simulations and observational data bundles from the ENA site provide an excellent opportunity for testing the parameterizations in SCMs used in large-scale climate and weather models. Parameterizations that would be most amenable to testing in SCMs include clouds, drizzle, shallow-convection representation, turbulent transports, and sub-grid variability. In the case of single-profile forcing for a periodic LASSO domain, this same forcing can be used to drive the SCMs. (Note: We have successfully managed to reproduce the characteristics (clouds, precipitation, boundary layer) of the 3D IFS model with the IFS SCM at the ENA site).

C.1.7 Potential Issues and Proposed Mitigations

One potential issue is the spin-up time needed to establish a realistic simulation for comparison with ENA observations. For small-domain LES, this spin-up time can be quite short, but for simulations in which we are hoping to evolve larger mesoscale structures with scales of tens of kilometers, the time required to reach the mature cell size may be quite long. This issue could be mitigated somewhat by starting the simulations sufficiently early to allow time for the mesoscale cellularity to develop appropriately. One possibility is nudging gently to the initial sounding while turbulence spins up (Yamaguchi et al. 2013). One problem is that sometimes when the nudging is stopped, the model can wander off in a different direction, rendering the approach challenging. More work should be done to determine ways to help establish mesoscale cellularity to develop in the simulations.

C.1.8 References (Maritime Scenario)

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C.2 Deep-Convection Scenario White Paper

LASSO Expansion Scenario

LASSO–Deep Convection (LASSO-DC)

A White Paper Submitted to the Atmospheric Radiation Measurement User Facility

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C.2.1 Short Description

Whereas the current Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO; https://www.arm.gov/capabilities/modeling/lasso) project is dedicated to the study of fair-weather cumulus over ARM's Southern Great Plains (SGP) site, here we propose an expansion of the project to the development of deep convective cells observed at SGP and/or during ARM field campaigns. The current LASSO simulations use periodic boundary conditions and an ensemble of large-scale forcing data sets, but the proposed LASSO-Deep Convection (LASSO-DC) would use a mesoscale model with nested domains and include an ensemble of initial and lateral boundary conditions. Ensemble members with a good fit to observed convective evolution will be used to initialize and force the LES run on an innermost nested domain. We propose applying LASSO-DC to a set of convective events at SGP as well as ARM field campaigns elsewhere. The latter would target campaigns with a long enough duration (several months) to ensure a sufficient number of cases are simulated successfully.

C.2.2 Science Drivers

Moist deep convection is a key feature of the atmosphere, critical for earth's general circulation, regional weather and climate, and the hydrological cycle. Many aspects, including small-scale dynamics, microphysics-dynamics interactions, and upscale growth, remain uncertain despite decades of research — owing in part to both observational and computational limitations. ARM radar-intensive, ground-based measurements are a particularly well-suited resource for tackling some of the leading observational challenges (e.g., Fridlind et al. 2019). On the computational side, the ability to resolve individual convective updrafts and downdrafts and the associated turbulent eddies is critical for modeling features like the convective flow structure (e.g., Varble et al. 2014a), vertical transport and updraft mass flux (e.g., Bryan and Morrison 2012), and entrainment/detrainment (e.g., Bryan et al. 2003; Bryan and Morrison 2012; Lebo and Morrison 2015). However, because of limited computational resources, most modeling studies of deep convection have employed "convection-allowing" horizontal grid spacings of approximately 1 km or greater that inadequately resolve individual convective drafts and fail to resolve an inertial sub-range of turbulence, represented by a -5/3 slope of the kinetic energy spectra. For simulating mid-latitude deep convection using WRF, or models with similar numerics, resolving an inertial subrange at heights above the planetary boundary layer (PBL) requires grid spacings less than about 250 m (Bryan et al. 2003; Lebo and Morrison 2015). This has important implications for representing entrainment and mixing within convective drafts; WRF simulations using 500-m horizontal grid spacing showed much less updraft core dilution compared to higher-resolution runs (Lebo and Morrison 2015). Within the PBL, even smaller grid spacings are generally required to resolve an inertial subrange, often less than 100 m. The inability to realistically represent turbulence and resolve individual convective drafts in simulations using ~1 km horizontal grid spacing also impacts microphysical evolution and microphysics-dynamics interactions. For example, Bryan and Morrison (2012) showed large increases in evaporation occurred when the horizontal grid spacing was decreased from 1 km to 250 m, affecting accumulated surface precipitation and precipitation efficiency.

The need for high resolution to simulate these features is especially challenging for deep convection because it also requires a fairly large domain size. Thus, LES of deep convection is arguably more difficult from the standpoint of computational resources than other cloud regimes, such as stratocumulus or shallow cumulus in which smaller domain runs can still be useful.

Furthermore, significant sensitivity of deep convective properties to uncertain initial conditions and limited predictability at convective scales suggest that model ensembles should be employed to provide more robust conclusions. This further increases the computational expense beyond that available to most researchers. Again, this problem is particularly acute for deep convection compared to other cloud regimes, because limited predictability makes forecasting convective initiation at even roughly the correct time and region often difficult. Both of these issues can be ameliorated by LASSO-DC, which would provide LES output synergistically combined with ARM observations to the research community, along with initial condition and forcing files that can be used for further simulations by users. We argue that the proposed LASSO-DC framework (detailed in the sections below) is particularly well suited to addressing these challenges, and the data sets it will provide would be a unique resource to the broader community for studies of deep convection.

Another challenge using convection-allowing models is uncertainty in updraft microphysics. Owing to large uncertainties associated with, for example, fundamental processes such as ice initiation and growth (e.g., Fridlind et al. 2017, and references therein), great priority is now placed on advancing observational constraints on model simulations. Remote sensing is generally the richest observational data source, especially for deep convection over land.

However, state-of-the-art and research-grade products (such as multi-Doppler wind retrievals or polarimetric rain size distribution parameter retrievals) often involve substantial case-by-case quality checks, which limit the number of case studies that retrieval teams can supply. On the other hand, if regional simulations are unable to successfully capture an observed case (for example, because of the inherently limited predictability), laborious retrievals may not receive wide use for that case. LASSO-DC can address this model-observation bottleneck by using ensembles at coarser resolution to establish which cases from SGP or ARM field campaigns can be successfully simulated from the perspective of reasonable timing and location of deep convective initiation. The LES component of LASSO-DC will be run for these cases. This can help focus the modeling and retrieval communities on the same set of cases, ensuring overlap between retrieval and observational analysis efforts and modeler use of ARM data products.

The basic goal of LASSO-DC is to provide a set of "nature runs" using LES to augment SGP and ARM field campaign observations in comprehensive data bundles. These data are intended to be used by researchers to investigate critical yet uncertain aspects of deep convection that require explicitly simulating flow at LES scales. These include, but are not limited to:

- Convective cloud dynamics (thermal-like structures, updraft strength, and entrainment/detrainment in particular) and the relationship to critical features like updraft and downdraft mass fluxes, vertical transport, and the shallow-to-deep convective transition.
- Cold pool interactions with the surrounding environment and convective drafts in turbulent flow.
- Microphysics-dynamics interactions, especially in the context of cloud-scale eddies and smaller-scale turbulence.
- Improved understanding of aerosol-convective cloud interactions, which are complicated by factors such as turbulence and entrainment/detrainment.

In addition to studies addressing these fundamental aspects of deep convection, the LASSO-DC data sets are intended to be used for physics parameterization development and testing (i.e., planetary boundary layer and convection schemes), and evaluation of larger-scale models.

To briefly summarize, LASSO-DC will provide:

1. A set of observationally based case studies from SGP and ARM field campaigns using the ensemble methodology described below. These cases will be selected based on the ability to reasonably simulate convective initiation and evolution at approximately the correct time and region, and the availability of sufficient observations. These cases are expected to help focus synergistic modeling and observational analysis/retrieval efforts within the community.

2. Combined LES and ARM observational data bundles for the selected cases. These data are intended to be used by researchers to address fundamental science questions on deep convection, to develop and test physics parameterizations in weather and climate models, and to evaluate larger-scale models. Model setup and initial/forcing condition files will be provided in the data bundles so that modelers can easily run their own simulations for the same cases, facilitating collaboration among researchers.

C.2.3 Full Description

We advocate running LASSO-DC for specific cases from recent or future deep convection-focused ARM field campaigns (e.g., CACTI, TRACER), as well as targeted cases from SGP (e.g., A. Shapiro IOP, 2018 SGP X-SAPR process-oriented scan experiment).

Several factors motivate this approach. First, there is a strong science motivation to study convection at multiple locations because of the geographical variability in meteorology and deep convective life cycle. For example, deep convective evolution will likely differ between SGP (with convective initiation often associated with mesoscale boundaries), coastal regions with sea breeze-triggered convection (i.e., as expected during TRACER), and regions with a significant terrain influence on initiation (i.e., as in CACTI). In fact, one could argue that by conducting field campaigns at various locations around the world with a consistent suite of instrumentation, ARM is uniquely poised to study how convection varies across these different regimes. *This unique capability of ARM could be strongly augmented by combining these field campaign observations with LES from LASSO-DC.* Second, quality-controlled scanning precipitation radar retrievals are necessary from both complementary product and model evaluation perspectives. However, such retrievals are confined almost exclusively to field campaign or IOP periods with limited instrument downtime and sufficient quality control of data. Third, model and observational data bundles from well-studied and observed field campaign or IOP cases in which deep convection is the target are more likely to be used by researchers. Supporting this point, we note that ARM field campaigns focused on deep convection (e.g., the Tropical Warm Pool-International Cloud Experiment [TWP-ICE], the Midlatitude Continental Convective Clouds Experiment [MC3E], the ARM MJO Investigation Experiment/Dynamics of the Madden-Julian Oscillation [AMIE/DYNAMO], the Green Ocean Amazon 2014/15 [GoAmazon] campaign) have received considerable attention in the research community, evidenced by a large number of related publications (over 400 to date[1]) and the success of model intercomparison studies centered around observationally based cases from these campaigns (Varble et al. 2011; Fridlind et al. 2012; Zhu et al. 2012; Varble et al. 2014a,b; Wang et al. 2015; Fan et al. 2017; Li et al. 2018; Bin et al. 2019). We also anticipate that LASSO-DC will facilitate additional collaboration between modelers and observationalists by focusing the community on specific field campaign cases. This tends to happen eventually for field campaigns, but this process would be greatly facilitated by LASSO-DC. This would also help to focus the observational community on developing and improving retrievals for specific cases, promoting synergy between modeling and observations.

A case-study focus instead of routine LES is recommended. This is because of the difficulty of simulating many specific convective events given their sporadic nature and limited predictability in the absence of a convective-scale data assimilation effort, which we recommend avoiding so that the LES is free running and only forced at the lateral boundaries. In other words, there will likely be strong sensitivity to initial conditions for many cases owing to inherently limited predictability. To address this concern, we recommend first using lower-resolution (2.5-km horizontal grid spacing),

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[1] 138 publications related to MC3E, 167 for TWP-ICE, 71 for GoAmazon, and about 100 for AMIE.

~10–15-member ensembles with perturbed initial and lateral boundary conditions to identify suitable cases and forcing data. Ensemble members using the lower-resolution model that produce the most realistic convective initiation and evolution based on an automated, objective evaluation will be selected to initialize and force a "mini-ensemble" of the LES (detailed below). This contrasts with the current LASSO project that is focused on running ensembles with perturbations to forcings (which are derived from a combination of observational and model sources), but not initial conditions (which are taken as well-observed over the small domain).

Because of the significant challenge of modeling upscale growth and evolution of organized convective systems within a limited-domain LES (~150 x 150 km^2), we recommend focusing on the life cycle and behavior of initiating and initially isolated deep convective cells that are often strongly diurnally driven. This also aligns well with the research questions and motivation outlined in Section C.2.2. Although upscale growth and organization of deep convection is a critical problem, early-stage isolated deep convection presents a simpler picture for studying fundamental behavior of convective dynamics and microphysics that can be more easily explored using LES with a relatively small domain. In addition, this can provide foundational knowledge for studying more complex, mature systems. Note that this focus would not preclude cases of convective initiation later growing upscale into organized systems. For such cases, LASSO-DC would focus on the initiation and early stages of evolution when cells are more isolated. Based on a recent study of mesoscale convective system (MCS) climatology over the U.S., Feng et al. (2019) showed that the initiation of convective cells organizing later into an MCS is a common occurrence over SGP during spring, comparable to that over western Oklahoma and the Texas Panhandle associated with initiation along the dry line. Thus, we expect some LASSO-DC cases from SGP to be of this type.

With an appropriate model configuration and outputs, we envisage a wide range of LASSO-DC users including both observationalists and modelers of precipitation, microphysics, and dynamics. Furthermore, although ARM and ASR have a climate focus, there are many issues common to weather and climate models related to deep convection. For example, the science drivers listed above are of interest to both weather and climate communities owing to their fundamental importance to both precipitation and radiative fluxes. Moreover, parameterization development (including convection schemes) often involves common issues for climate and numerical weather prediction models, especially as common modeling frameworks are emerging to address both.

The LASSO-DC ensemble framework would also be uniquely suited to testing the "simulate-ability" of some target number of well-observed events, which can be extremely challenging for most researchers working within limited computational and time constraints. This framework could accommodate either smaller LES ensembles over a larger number of case studies, or larger LES ensembles within a smaller set of cases, depending upon specific field campaign outcomes. LASSO-DC would relieve multiple research groups from the burden of repeating similar ensembles on their own, thus reducing program-wide duplications of work effort, and would make it possible for more researchers to reasonably perform high-resolution simulations because they can get a head start by simply downloading an already-vetted setup for their own use.

C.2.4 Model Configuration

Details on the model forcing can be found in Section C.2.5. LASSO-DC will use a nested WRF setup regardless of case location. Previous studies have shown that 250 m is approximately the grid spacing at which mid-latitude deep convective flow becomes turbulent and individual drafts become resolved, in WRF or models with similar numerics (Bryan et al. 2003; Bryan and Morrison 2012; Lebo and Morrison 2015). However, finer resolution is generally required to resolve eddies within the PBL, keeping in mind that a grid spacing 5–7 times smaller than a given feature is required to resolve that feature using WRF. Thus, we recommend approximately 100-m grid spacing. This is within the resolution range to resolve mid-latitude deep convective drafts and an inertial subrange at heights above the PBL (Bryan et al. 2003; Lebo and Morrison 2015), while being at the edge of resolving large PBL eddies (for typical PBLs ~1-km deep). We recommend equal horizontal and vertical grid spacings through most of the troposphere, which is consistent with the inherently three-dimensional structure of turbulent eddies. Comparable horizontal and vertical grid spacings are also more consistent with the design of LES subgrid-scale closures than highly anisotropic grids. Thus, horizontal and vertical grid spacings of ~100 m are recommended for the innermost domain, with two exceptions: 1) stretching of vertical levels above the tropopause to limit computational expense; 2) addition of a few “extra” vertical levels in the lowest 100 m to ensure there are levels within the surface layer, which is important for surface coupling.

To encapsulate deep convective cells sufficiently, and given the inherently limited predictability of convective initiation, we advocate a ~150-by-150-km^2 horizontal domain size and a 25-km top that is necessary for deep convection that can occasionally reach 20-km altitudes. The location of the LES domain will be necessarily dictated by the location of ARM field observations, whether at SGP or field campaign locations. Vertical grid spacing can be stretched at upper levels, particularly above the tropopause, such that the number of vertical levels can be held to ~150. This configuration will maintain efficient parallel computing efficiency. With a 5:1 nesting ratio, two outer domain sizes will be ~250 by 250 km^2 and 1500 by 1500 km^2 with 500-m and 2.5-km horizontal grid spacings, respectively. Small random perturbations will be continuously applied along the outermost ~100– 200 grid points in the ~100-m LES and 500-m inner domains to facilitate spin up of turbulence; this is now a standard approach using WRF nested down to LES scales.

We envision running a “mini-ensemble” with a limited number (1–5) of LES runs for each case, with the exact number of ensemble members depending upon available resources. These members will be forced by different initial and lateral boundary conditions obtained from the outer 2.5-km grid spacing domain ensemble, determined by which of the 2.5-km domain members produce the “best” results relative to observations (see Sections C.2.5 and C.2.6). This mini-ensemble approach is particularly attractive, as opposed to a deterministic approach, because of the limited predictability of deep convective initiation and the potential for deep convection timing and location to change somewhat between coarse and high-resolution runs. The ensemble size will need to be more limited than the current LASSO shallow cumulus ensembles because of the need for a significantly larger domain when considering deep convection. Simulation lengths for the *outermost* WRF domain are envisioned to be approximately 24 hours. This will provide initial and lateral boundary conditions for the inner LES domain, which will be run for a shorter period focused on convective initiation and evolution of isolated cells (i.e., before possible upscale growth). In terms of model physics, a boundary-layer parameterization (e.g., YSU or MYJ) will be used in the outer two domains (2.5-km and 500-m) but will be turned off on the innermost domain wherein the TKE-based subgrid-scale mixing scheme in WRF will be used.

We suggest the possibility of running a limited-member multi-physics ensemble depending on available resources. However, such a multi-physics ensemble should only be run in the "best-case scenario" in terms of computational resources, and otherwise should be lower priority than the LES mini-ensemble with varying initial and lateral boundary conditions. Because all initialization and forcing files will be provided as part of the data bundles, users would be able to rerun simulations with other physics options or (as discussed below) aerosol perturbations. The surface scheme can affect surface fluxes that influence boundary-layer evolution and strongly modulate convective cloud life cycle. The microphysics scheme also strongly influences cloud life cycle and key processes such as ice initiation, precipitation initiation, and phase changes that feed back to convective cloud dynamics. For microphysics, we recommend schemes that are connected to existing radar and satellite simulators (e.g., Thompson, Morrison, Thompson-Eidhammer). Moreover, the Thompson-Eidhammer aerosol-aware scheme (Thompson and Eidhammer, 2014) is recommended because it can represent cloud-aerosol interactions in a physically based way with limited computational cost. This scheme can pull in aerosol information from global analyses such as the Goddard Earth Observing System Model, Version 5 (GEOS-5) and/or ARM surface-based and aircraft measurements. We leave open the possibility, depending upon resources, for including a few runs of a given case using aerosol perturbations. This proposed configuration will not include complex chemistry like that found in WRF-Chem, as this would involve far too much computational expense. Again, this would be lower priority than the LES "mini-ensemble" with varying initial and lateral boundary-condition forcings.

Standard model output is motivated by both LES evaluation via measurements and LES products that fill critical gaps in available observations. For deep convection, primary gaps are high-resolution, 3D evolution of convective dynamics and microphysics including variables that impact them. 3D output requires significant storage resources and the frequency at which it is written impacts the computing time for simulations. Therefore, we recommend that standard WRF state variables, hydrometeor mass and number mixing ratios, latent heating, Rayleigh radar reflectivity, TKE, and cloud condensation nuclei concentration (if using aerosol interactive microphysics) be output over the duration of convective events at the highest time frequency that is feasible given data storage resources, preferably at least every 5–20 min. This could be mitigated in an automated way by outputting 5–20-min, 3D data only during and after convective initiation, with hourly 3D output data prior. Shifting to higher-frequency 3D output could be based on automated in-line calculation of cloud-top heights and vertical velocities to diagnose convective initiation, for example. Many process rates can be very well estimated through offline computations using the standard model output. However, an exception is cloud water condensation/evaporation and homogeneous freezing of cloud water and rain. Thus, we recommend adding these to 3D output. WRF restart files (every 30 to 60 min) will allow users to rerun specific periods with higher-frequency output or additional outputted variables should they so desire. Thus, it will be important to include restart files within the data bundles.

Direct calculations of entrainment and detrainment (e.g., Romps 2010; Dawe and Austin 2011), and tracking of convective thermals and their properties (e.g., Hernandez-Deckers and Sherwood 2016) are of particular interest for studying deep convective dynamics and microphysics. However, such calculations require either very high time-resolution 3D output (up to every ~10 sec), which is not feasible over long durations, or in-line calculations that are not yet publicly available in WRF and cumbersome to implement. In-line calculations could be added and would be of benefit to LASSO-DC, but we do not anticipate ARM having the resources to do this. In lieu of this, required 3D variables to calculate entrainment and thermal tracking (i.e., wind and pressure fields, total cloud condensate, potential temperature) could be output for short periods (10–15 min) around key times for convective events at the required high frequency of every ~10 seconds (note that these time periods would be constrained by the availability of restart files). These time periods could be automatically identified in post-processing, for example, by statistics of cloud, vertical velocity, and/or radar echo-top heights. Inclusion of restart files within the data bundles would also allow users to rerun short periods with higher-frequency output for entrainment and thermal tracking calculations. We additionally recommend researching the potential for quilting output to cut down on computing time and possibilities for file size reduction. NASA has a 2–3x file compression method that could be implemented and Unidata is working on adopting a LOSSY format that allows up to a 30 times reduction in file size. While these methods could be particularly useful for these frequent, large-output files, we argue that they would also be useful for any LASSO runs given the potential for increasing output frequency without increasing total output size.

For tracking of convective cloud evolution and evaluation of the LES with observations, we advocate for higher-frequency 2D and one-dimensional (1D) output of specific variables. An ensemble of points across the domain will be chosen for sub-1-minute 1D (vertical profile) output of:

- Pressure
- Potential temperature
- Water vapor mixing ratio
- Horizontal and vertical wind
- Hydrometeor mass and number mixing ratios, mass-weighted mean size, and both mass-weighted and reflectivity-weighted mean fall speeds
- Latent heating/cooling rates
- Rayleigh radar reflectivity.

From this output, direct comparisons can be made with available radiosonde, Interpolated Sounding VAP (INTERPSONDE), Merged Sounding VAP (MERGESONDE), radar wind profiler (RWP), sodar, Doppler lidar, AERI, and Raman lidar retrievals of thermodynamic and kinematic conditions. Although these observations typically only exist at a single location that may not be representative, the ensemble of model profiles will allow the observed profiles to be placed into context of a more representative sample. These variables can also be combined to simulate cloud boundary information that is comparable to KAZR2 Active Remote Sensing of Clouds VAP (KAZR2ARSCL) and RWP retrievals.

One-minute 2D horizontal slice output will include:

- Surface rain rate and mass-weighted mean drop size (comparable to scanning radar retrievals and gauge/disdrometer measurements)
- Lowest model level and/or 1-km height and composite (column maximum) Rayleigh radar reflectivity (comparable to scanning radar retrievals)
- Precipitable water vapor (comparable to microwave radiometer, Global Positioning System, and geostationary satellite retrievals)
- Surface sensible, latent, and radiative fluxes (comparable to eddy correlation flux and upwelling/downwelling radiometer measurements)
- Soil temperature and moisture (comparable to surface energy balance system)
- Top-of-atmosphere (TOA) radiative fluxes (compare to geostationary satellite measurements)
- Convective indices including most unstable convective available potential energy and inhibition (MUCAPE/CIN), lifted condensation level (LCL), level of free convection (LFC), level of neutral buoyancy (LNB), and vertical wind shear over 0–1-, 0–3-, and 0–6-km layers
- Zonal, meridional, and vertical wind speed, temperature, water vapor mixing ratio, and hydrometeor mass and number concentrations at every kilometer height including the surface
- Liquid water path, ice water path, and cloud base and top heights/temperatures defined using Greg Thompson's in-line ceilometer and GOES simulator code compatible with the Rapid Radiative Transfer Model for Global Climate Models (RRTMG) scheme or using condensate mixing ratio thresholds (comparable to geostationary satellite, stereo camera, and microwave radiometer retrievals)
- Surface aerosol or cloud condensation nuclei (CCN) concentration or particle size distribution (PSD) (if simulating aerosol evolution; comparable to condensation nuclei (CN), CCN, and size distribution measurements)
- Aerosol optical depth (if simulating aerosol evolution outside of WRF-Chem; comparable to Cimel sun photometer, multifilter rotating shadowband radiometer (MFRSR), and satellite retrievals)

These fields will also allow for tracking of individual convective cloud evolution that links with tracking of radar- and satellite-observed convective clouds without high -frequency 3D output.

An option will be made available to output 2D vertical slices at a frequency that matches scanning radar range-height indicator (RHI) scans if available for a given case. This output will include u, v, w, and hydrometeor PSD information along observed radar RHI azimuths at several simulated radar locations in the model to cover uncertainty in the location of deep convective initiation and growth. This output can then be post-processed through a radar simulator to produce reflectivity, radial velocity, specific differential phase, and differential reflectivity that are comparable to the same fields in radar observed RHIs. Like previous output linking to observations, this provides a direct linkage between LES output that includes information not accessible in observations and fields that are directly observable.

We do not recommend in-line domain mean output since this would significantly slow computations. Such quantities can be computed in post-processing, if warranted.

We recommend several trade-offs to balance the computational and data storage costs. First, as we argue, it is important to use approximately 100-m horizontal and vertical grid spacings and a large enough domain (horizontally and vertically) to capture cell evolution. This arguably presents greater computational challenges than simulating (unorganized) shallow convection or stratocumulus, particularly in terms of output storage. Because of this, we suggest a limited number of ensemble members with varying initial and lateral boundary conditions, or using different surface parameterizations or microphysics schemes. Getting the most “bang for the buck” in terms of limited-size ensembles will be facilitated by objectively selecting those members that produce the most realistic convection in the outer WRF domain, and only using these members to force the LES inner domains. Unfortunately, it is not feasible to output 3D LES fields at high temporal frequency, and to balance this cost we recommend relatively infrequent 3D output (every 5–20 min) but much more frequent 1D and 2D output as detailed above. We also advocate for outputting high-temporal-frequency (~10 sec) 3D data over selected short periods using restart files in order to obtain data for explicitly calculating entrainment rates and thermal tracking.

Although we recommend a triply nested WRF configuration, by far the greatest cost (by at least an order of magnitude) will be the innermost LES nest. This will consist of approximately 1500 x 1500 x 150 grid points, and a time step of order 1 sec. The exact computational cost will of course depend on the system, compiler, number of cores, etc.

C.2.5 Input Data such as Initial, Forcing, and Boundary Conditions

As discussed above, we recommend a multi-step ensemble approach centered on selected cases from ARM field projects and the SGP:

1. **In the first step**, *ensembles of the 2.5 km, 1500x1500 km^2 outer domain will be run using WRF with various initial and lateral boundary conditions.* We recommend using a broad range of analyses for initial and lateral boundary conditions, in order to represent spread and uncertainty to the fullest extent possible. Specifically, we recommend forcing with the 21-member GEFS ensemble, as it is straightforward to use and available globally (thus, it can be used for SGP and any field campaign cases). Ensemble ECMWF Integrated Forecast System (IFS) analyses can also augment this forcing for SGP and field campaign cases anywhere around the globe. Finally, forcing is available from the hourly deterministic High-Resolution Rapid Refresh (HRRR) model for U.S.-based cases, which is attractive given its 3-km grid spacing and use of Thompson microphysics, which aligns with the proposed setup for the outer 2.5-km LASSO-DC domain. Moreover, the HRRR uses radar data assimilation that can help constrain upstream conditions. The fact that Global Ensemble Forecast System (GEFS), ECMWF, and HRRR analyses

have drastically different resolutions helps motivate a large outer domain (1500 x 1500 km^2) for LASSO-DC, such that spin-up along the lateral boundaries will have little impact on the inner domain region that will force the LES nest. HRRR analyses only provide initial/lateral boundary conditions for single ensemble members. Nonetheless, when combined with GEFS and ECMWF, we anticipate sufficient spread to capture convective initiation reasonably well for many convective events. We also note that spread could be increased by applying GEFS or ECMWF IFS perturbations (i.e., the difference in a field between a GEFS member and the ensemble mean) to the HRRR or ECMWF fields. We recommend simulation start times initialized from global analyses during the evening or overnight hours before the event of interest because: (i) the forcing files (e.g., from GEFS) are typically infrequent; (ii) at least ~4–6 hours of simulation time from a cold start is needed prior to deep convective initiation; (iii) a reasonable representation of morning cloud cover is often important for the next day's convective initiation.

2. **In the second step**, *objective evaluation of ensemble members* (see Section C.2.6 below) will determine which members (if any) produce results reasonably close to observations. *The initial and lateral boundary-condition files for these members would be provided as part of the LASSO-DC data bundles* so that researchers can rerun the cases using different physics options, or other sensitivity tests, or to facilitate output at a higher time frequency (e.g., for direct entrainment calculations as discussed in Section C.2.2). If no ensemble members meet the criteria of a "successful" simulation, then LES will not be run by LASSO-DC for that case.

3. **In the third step**, initial and lateral boundary conditions from the selected ensemble members will be used to initialize and force the inner 500-m and ~100-m nests of the LES mini ensemble. The inner nests will be initialized about 2–3 hours before deep convective initiation occurs in the 2.5-km domain (defined by reflectivity exceeding some threshold, i.e., "first echo") and run until approximately evening local time (~7–9 pm) to capture the life cycle of diurnally forced, isolated convection. We recommend simply rerunning the outer 2.5-km grid spacing domain together with the inner nests, such that forcing from each time step of the outer domain would be directly input into the 500-m domain. This is suggested, as it will remove a potential source of uncertainty/bias from interpolating relatively infrequent lateral condition files from the 2.5-km domain using the alternative "ndown" approach in WRF. Moreover, the computational cost of rerunning the 2.5-km domain is small (at least an order of magnitude smaller than a single run with the innermost LES domain). Furthermore, initial and lateral boundary-condition files would only be needed for the 2.5-km outer domain in the data bundles for modelers to rerun these cases, which greatly limits the total amount of data required in the bundles. We suggest running 1–5 LES ensemble members with varying initial and lateral boundary conditions per case, depending on computational resources available and the number of members from the 2.5-km outer domain ensemble that reasonably represent observed convective initiation and evolution based on the objective evaluation.

We do not recommend explicitly applying data assimilation to any of the model domains. For the inner high-resolution domains, free-running simulations are needed to address the basic science objectives. For the outer 2.5-km grid spacing domain, data assimilation could be employed but is not recommended owing to the significant complication this would add. This would present particular challenges when applying LASSO-DC to cases from various sites and field campaigns, in which availability of data to assimilate would vary widely. This would therefore make LASSO-DC much less "turnkey." The lack of data assimilation would be ameliorated by the proposed ensemble approach using various initial and forcing conditions for the outer domain based on analyses (e.g., GEFS). Thus, overall we feel that although a data assimilation component could be incorporated, the benefit would not be worth the cost.

For aerosol forcing, we recommend starting with a relatively simple approach to be determined during the LASSO-DC setup. While some WRF simulations have ingested multi-modal aerosol profiles derived from observations (e.g., Fridlind et al. 2017, for MC3E convection), the approach of initializing the aerosol fields from observations and allowing them to be transported and scavenged is not standard in WRF. Instead, LASSO-DC could adopt simpler options for “clean” or “polluted” simulations, such as specifying different cloud droplet number concentrations or background aerosol concentrations. Another option is to use the Thompson-Eidhammer aerosol-aware scheme (Thompson and Eidhammer, 2014), which allows aerosol-cloud interaction questions to be addressed in a physically plausible manner with a limited computational cost. As noted in Section C.2.4, this scheme can use information from global analyses (e.g., GEOS-5) and ARM surface and aircraft measurements.

C.2.6 Evaluation Data and Approach

A key requirement for LASSO-DC activities is the development and routine delivery of data bundles that include a suite of observations used for evaluating the fidelity of convective simulations. One goal for data bundles is to allow users to quickly evaluate simulation performance and select appropriate runs for research needs. Data bundles are expected to follow ARM file formats, with similar processing performed on observations to simplify reproduction of LASSO-DC materials.

We do not anticipate ARM observations will be included as part of LASSO-DC specifically for data assimilation purposes. Because we want the inner LES nest to simulate convective initiation “naturally” from its pre-convective environment, specified from the 2.5-km outer WRF domain, we recommend not assimilating ARM observations (or other observations). For reproducibility of LASSO-DC events, model initial and lateral boundary-condition forcing files will be provided in the data bundles, as well as appropriate information to access required observational forcing data sets.

Case selection will be linked to observations in the data bundle through LASSO data browsers and web-based visualization tools. Several ARM instruments are considered critical to case selection and subsequent model forcing, diagnostic, and skill score requirements. These ARM instruments and datastreams include, but are not limited to, a longer-wavelength scanning weather radar (e.g., the C-Band Scanning ARM Precipitation Radar [CSAPR2]) and a timely (pre-convective) radiosonde launch (e.g., ARM’s balloon-borne sounding system [SONDE]) in relatively close proximity to the deep convective initiation event. As ARM observations alone are not expected to satisfy the needs of the deep convective community for optimal LASSO-DC impact, we anticipate that observations external to ARM will be included, such as geostationary satellite retrieval products, operational long-wavelength scanning radar (e.g., Next-Generation Weather Radar [NEXRAD] or equivalent outside of U.S.), surface meteorological data (e.g., Mesonet), and additional aerosol characterization options. These external data will likely be important constraints for case selection. As these particular observations are not directly collected by ARM or required for LASSO-DC evaluation, we recommend they are included in the data bundle as much as available resources and logistics permit.

Owing to the anticipated difficulty in simulating deep convection because of limited predictability, model evaluation will follow a two-stage approach designed to encourage viable LES LASSO-DC runs. The first evaluation phase will analyze the coarser 2.5-km grid spacing WRF ensemble. An automated objective analysis method based on diagnostics and skill scores associated with these simulations will be used to identify 1–5 ensemble members most likely to encourage LES success for a given case. Model simulations are not expected to produce deep convective initiation, growth, and decay at the same time and location as observed owing to fundamental predictability limits. Thus, convective cloud statistics within the region of the 2.5-km grid spacing domain corresponding to the LES domain surrounding the primary ARM measurement site will be used to determine which ensemble members are “best” in reproducing the observations. These statistics will primarily rely on scanning precipitation radar observations, as highlighted below. A second concise LES simulation evaluation phase will follow.

Diagnostic plots and time series skill scores for both the 2.5-km grid and LES domain evaluation phases will be generated based on comparisons with ARM radar retrievals at the updating frequency of the retrieval, somewhat similar to previous LASSO evaluations. For LASSO-DC, initial radar-based comparisons are recommended to include (i) areal rainfall accumulation, (ii) rainfall rate distribution behaviors (max/min, percentiles), (iii) domain area fraction precipitation time series (e.g., area occupied by precipitation rates above threshold values), and (iv) time series of cloud echo-top height. The aforementioned observations may be estimated based on ARM scanning precipitation radar (e.g., CSAPR2, XSAPR) availability for an approximate 150 x 150-km^2 domain centered on the SGP site or AMF location. These products do not require forward radar simulators for modest success. The variables used for the comparisons may be optimized during LASSO-DC testing phases for better comparisons of observational and model products. Initial satellite retrieval-based comparisons are also recommended to include domain area fraction of cloud-top heights exceeding thresholds values and cloud-top temperatures below threshold values. Scores are also anticipated to track phase (lag correlation) as well as amplitude performance. Future diagnostics may include additional cell properties (e.g., cell size and number as a function of time based on contiguous radar reflectivity, rain rate, and/or cloud-top objects) and object-based verification packages as based on scanning radars and future availability of tracking codes.

C.2.7 Potential Issues and Proposed Mitigations

Modeling deep convection presents some unique challenges compared to other cloud regimes (e.g., stratocumulus or shallow cumulus). While LASSO-DC will need to confront them, at the same time these challenges limit the ability of the broader community to perform LES of observationally based deep-convective cases. Thus, LASSO-DC faces challenges but also presents considerable opportunity, as it can provide unique data products to the community that are difficult if not impossible for others to generate.

We focus on two key issues, and strategies for mitigating them:

1. As noted throughout this paper, modeling deep convection faces an inherent challenge owing to limited predictability of convective cell initiation and evolution. Thus, we expect some difficulty in representing convection within the LES domain for many cases. Our main approach for mitigating this issue is to first run ensembles at lower resolution (2.5-km horizontal grid spacing) with varying initial and lateral boundary conditions to determine which conditions are likely to produce convection within the LES domain. Using the widest spread of plausible initiation/lateral boundary conditions from ensemble analyses, we are hopeful that convective initiation will be captured for many cases. An important point is that evaluation of the 2.5-km grid spacing ensembles and selection of ensemble members to force the LES would be automated, reducing cost and overhead. This will also facilitate running LASSO-DC cases not only for SGP, but also for ARM field campaign cases. We feel that *extending LASSO-DC beyond the SGP domain is essential*, being critical from science needs to understand convective behavior in different regimes, to achieve wide interest from ASR scientists and the broader community, and to maximally leverage ARM observations collected from around the globe.

2. Data storage requirements in the face of limited resources are a challenge for any project running LES for multiple cases, but this is particularly true for deep convection. Modeling deep convection necessitates larger domains compared to other cloud types such as shallow convection. This can be mitigated somewhat by outputting select 1D and 2D quantities within the domain, as we detail in Section C.2.4, which can be done at high temporal frequency. Nonetheless, science requirements dictate saving 3D output, and we recommend this be done with a frequency no less than every 5–20 min. Approaches could be implemented to help mitigate this issue, such as outputting high-frequency 3D data only from the time of deep convective initiation, defined objectively as occurring, for example, based on in-line calculation of cloud, vertical velocity, and/or echo-top heights. In general, we recognize that the precise frequency of this 3D output will depend on availability of resources.

A key science motivation for running at ~100-m grid spacing is the ability to explicitly represent aspects of turbulent convective flow. For deep convection, this has important implications for modeling entrainment/detrainment and updraft core dilution, which are critical aspects of moist convective dynamics. Some features of turbulent convective flow can be analyzed from the standard 3D output at 5–20 min intervals. However, direct calculations of entrainment/detrainment and thermal tracking, which are likely to be of interest to many users, require cumbersome in-line calculations or extremely frequent output (every ~10 sec). Code for in-line calculations could be implemented into WRF if ARM has the resources to do this, which seems unlikely. In lieu of this, short periods of 15–20 min could be selected and run from restart files with output every ~10 sec. The selection of such periods could be automated similarly to the switch from hourly to every 5–20 min for standard 3D output at the time of convective initiation. Moreover, restart files will be included in the data bundles provided with LASSO-DC so that users could run from these restart files and generate whatever output suits their needs.

Success of LASSO-DC will be determined by two primary factors: 1) successful simulation of enough cases with reasonable convective initiation and evolution to make it worthwhile in terms of resource investment (targeting a minimum of ~10 cases per year); 2) community and user demand for LASSO-DC data bundles. Minimum requirements for assessing feasibility are 1) choosing potential cases; 2) availability of ensemble forcing from analyses (e.g., GEFS) for the outer 2.5-km grid spacing WRF domain for those cases; 3) quality-controlled observational data for objective evaluation of the outer domain ensemble members and LES runs, notably from scanning precipitation radar. Initial testing is recommended for cases from SGP and a recent (or near future) ARM field campaign. We feel it is important to test the approach for both SGP and field campaign cases, given the importance of extending the LASSO-DC project beyond SGP as noted above. CACTI is a good candidate for a recent ARM field campaign for retrospective deep convective initiation cases that are known to have high-quality precipitation radar data. A preliminary WRF run of a pre-CACTI case that nests down to 100-m horizontal grid spacing was already completed, showing that this approach is feasible in complex terrain. The upcoming TRACER campaign is a good candidate for the near future, for which Fridlind et al. (2019) demonstrate pilot study results using a simulation with 500-m horizontal grid spacing on the inner domain and NEXRAD observations. Finally, we note that if successful, this nested ensemble framework could be applied to future LASSO deployments for real case regimes besides isolated deep convection, going beyond the standard quasi-idealized lateral periodic boundary-condition LES setup. This approach would allow realistic mesoscale variability in the initial and lateral boundary conditions and a straightforward and realistic way to generate ensembles that is not possible with the standard LES setup.

Overall, to address issues related to data output size and output frequency, an initial advisory committee can make LASSO-DC recommendations that are likely to serve many users. Enough active users are now engaged in such studies that several advisers are likely to be available to offer reasonable judgments for a good starting approach.

C.2.8 References (Deep-Convection Scenario)

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C.3 Clear-Air Turbulence Scenario White Paper

LASSO Expansion Scenario

Cloud-Free Boundary Layer Turbulence

A White Paper Submitted to the
Atmospheric Radiation Measurement User Facility

Writing Team: William I. Gustafson Jr. and Larry K. Berg,
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C.3.1 Short Description

This LASSO scenario consists of simulations focusing on turbulence during cloud-free conditions to understand boundary-layer growth and decay, and energy, momentum, and moisture transfers between the land and atmosphere. Also of relevance is the behavior of the nighttime boundary layer. Because these types of conditions occur at all ARM sites, this scenario could be executed at any of ARM's observatories and for many of the field campaign deployments, provided that sufficient observations are part of the campaign. The SGP location is used as an example in this paper.

C.3.2 Science Drivers

Boundary-layer turbulence is a fundamental process controlling the transfer of moisture and energy between the land surface and atmosphere. Surface fluxes drive eddy formation, which in turn transfers moisture and energy away from the surface up into the boundary layer. Throughout the day, these eddies cause the boundary-layer top to rise. The boundary-layer growth is, in turn, limited by subsidence and entrainment of free tropospheric air at the top of the boundary layer, with the free tropospheric air typically colder and drier than within the boundary layer. As the sun sets, the land cools and the transfer of energy from the land to the atmosphere reverses, ultimately leading to a decay of turbulence and the top of the boundary layer sinking.

Monin-Obukhov similarity theory has been used to understand and simulate the surface layer for many decades, and this theory works reasonably well for statistically stationary turbulent conditions over a homogeneous surface. However, the theory does not do as well under conditions where the underlying assumptions no longer apply, such as in the presence of complex topography (e.g., Liang et al. 2014) and when the air is stably stratified (e.g., Schlogl et al. 2017; Mahrt et al. 2012; Kumar and Sharan 2012; Grachev et al. 2013). Various levels of complexity have been employed for parameterizing the boundary layer, with many involving simplifications of the governing equations that ultimately require making assumptions to close the system of equations. However, all existing efforts cannot properly represent the entire range of boundary-layer conditions from stable to well mixed. New theories and methodologies are needed to parameterize the full range of situations within weather and climate models. Improvements in this area would benefit many communities important to DOE, such as E3SM climate modelers, wind energy researchers and forecasters, and the overall weather forecasting user base and developers.

Parameterizations of boundary-layer turbulence applied in regional and global models are frequently based on measurements or simulations that have been normalized by the relevant boundary-layer scales such as the boundary-layer depth and the Deardorff convective velocity scale. An analysis of data collected using the Doppler lidar at the SGP site shows that the scaling breaks down during transitions periods in the morning and evening (Berg, Newsom, and Turner 2017), highlighting the need for new or revised parameterizations during these periods.

Low-level jets and their interactions with the boundary layer are an area of scientific inquiry that the SGP is particularly well suited to explore compared to the other ARM observatories (Berg et al. 2015). By focusing the LES simulations on nighttime and the transition periods at the end and beginning of the day, one can capture the presence of the low-level jet as it evolves and identify interactions between the jet and surface-driven turbulence (e.g., Duarte et al. 2015). Improving process understanding in this area will be useful for improving boundary-layer parameterizations and improving simulations of elevated convective initiation.

C.3.3 Full Description

Cloud-free boundary-layer transitions and stable conditions occur around the world, so LASSO could be employed for clear-air turbulence at any ARM site, provided sufficient instrumentation exists for partnering with the LES. SGP is a good location and will be used for discussion purposes. SGP has the advantage of a strong diurnal cycle (as opposed to the damped diurnal cycle associated with long days and nights at the North Slope of Alaska [NSA]) location combined with the land surface (as opposed to the temporally damped maritime surface over the ocean and land-sea breeze circulations at the ENA location) that, taken together, provide a predictable, routine environment for studying surface forcing and its impact on boundary-layer turbulence since every day exhibits a similar cycle between mixed and stable conditions, at least when the synoptic environment is not significantly changing. So, when clear conditions prevail over multiple days, one can have at least one transition from turbulent to stable conditions each evening and vice versa in the morning. In between the transitions, the nighttime boundary layer can be simulated to assist with boundary-layer parameterization development.

The LES modeling of clear air and nighttime conditions will add value to ARM's observations by providing insight into interactions at the top of the boundary layer where remote retrievals often have difficulty showing time-resolved details. For example, Doppler lidars require aerosol particles for backscattering light, but aerosol concentrations typically have strong gradients near the top of the boundary layer, with many fewer particles in the free troposphere. Thus, the signal degrades in the region of most interest when one attempts to study entrainment processes at the boundary-layer top. In comparison, the LES will provide a statistical representation of this interface region, and the model can be enhanced to output specific details, such as entrainment rates.

C.3.4 Model Configuration

Many of the model configuration details for a clear-air turbulence scenario could build upon the current LASSO implementation for shallow convection. The forcing ensemble would still be relevant along with the traditional LES approach. Changes that would be needed involve tailoring the LES for the process of interest and using observations to evaluate turbulence and the boundary-layer structure instead of clouds.

Two possible domain configurations could be used for this scenario. The first could use the traditional LES approach with doubly periodic lateral boundary conditions. Choosing this option would be appropriate for science foci on turbulent structures that are relatively small in scale, on the order of 1 km, and regional variability would not be a priority. Because of the lack of clouds, the domain can be smaller than for the shallow-cumulus scenario. For this clear-air scenario, a domain around 12-km wide should be sufficient, but this will need to be tested. The second domain option would use a nested LES domain, which would enable additional scientific foci around issues of surface heterogeneity plus the ability to include additional physical processes related to low-level jet formation that require sloped terrain (Shapiro, Fedorovich, and Rahimi 2016). A nested domain would need to be larger than a periodic domain to both permit spin-up of the turbulence as well as to contain the regional heterogeneity that would drive this choice. The exact size would need to be tested, and it would likely be around 25 km across.

Given that the scientific requirements be met, cost will be a strong consideration for the domain size. Additionally, the resolution would need to be increased compared to the shallow-cumulus scenario to properly represent the nighttime stable conditions. Horizontal grid spacing would need to be around 25 m with vertical grid spacing around 10 m within the boundary layer, which at SGP can rise to several kilometers. Higher vertical resolution will be required very near the surface — around 2–5 m grid spacing. A model top around 6 km would be sufficient to capture the boundary-layer growth and decay, provided that the model sponge layer does not impinge on the boundary layer or air involved in boundary-layer-top entrainment. A possible difficulty is the frequent low-level jet that forms over the SGP, which would generally not be an issue at the other observatories. Properly capturing the impact of the jet on the boundary layer may require a deeper domain so that the jet can be established properly via the large-scale forcing. If the choice is made not to focus on jet conditions, one could attempt to choose cases that do not contain the nocturnal low-level jet.

The physics parameterization suite for this scenario can be simple given the lack of clouds. Surface fluxes would be specified from observations when using periodic lateral boundaries, as in the shallow-cumulus scenario. An interactive soil model would be a better choice if a nested domain is chosen. The Thompson microphysics scheme would be enabled for the occasional possibility of cloud or fog formation, but most cases would be selected for their cloud-free conditions. One could consider turning off all cloud processes, but that could leave the model open to occasional issues where supersaturations could form for small regions. Radiation would use the RRTMG radiation scheme, which permits using the standard atmosphere or specified radiative fluxes above the model top for handling the short model top. The sub-grid-scale (SGS) scheme is the one parameterization requiring more careful consideration.

The current shallow-convection scenario uses the Deardorff SGS scheme to handle the smallest turbulent scales. This works adequately for shallow convection. However, the clear-air scenario is specifically focused on the model's ability to represent the resolved turbulence and to capture nighttime intermittent turbulence. So, we would want as accurate a handling of the split between resolved and sub-grid turbulence as possible. A more accurate scheme, such as the nonlinear backscatter anisotropic scheme (Mirocha, Lundquist, and Kosovic 2010) or another dynamic SGS scheme, should be investigated to identify if the improvements are sufficient to warrant the added cost. One method that has proven useful for capturing intermittent turbulence is the dynamic Wong and Lilly model (Wong and Lilly 1994) combined with a reconstruction model (Chow et al. 2005). This has been used effectively with 25-m grid spacing for "real-world" nested LES cases with intermittent turbulence (e.g., Zhou and Chow 2014a, 2014b). Another alternative would be to use weighted essentially non-oscillatory (WENO) advection as an implicit LES SGS model (Pressel et al. 2017). This has the advantage of needing less case-specific tuning and is cheaper, yet the results are functionally similar to the dynamic SGS models.

One other consideration that will need to be investigated is the handling of the large-scale winds imposed upon the LES. The current methodology used with WRF for the shallow-convection scenario imposes an initial wind profile that is not modified throughout the model integration. This will likely need to be changed to capture the nighttime conditions at the SGP facility. Nocturnal low-level jets and associated shear-driven turbulence are common at the SGP, and these jets will interact with surface-driven turbulence to determine the state of the lower atmosphere. Therefore, if the WRF model is used with periodic boundaries and imposed large-scale forcings, the current handling of large-scale conditions for temperature advection, moisture advection, and subsidence will need to be enhanced to include the ability to prescribe time-dependent large-scale pressure gradients to represent the large-scale wind conditions. This would not be an issue with a nested domain since the winds would be handled consistently across the boundaries.

The cost of the suggested domain and physics configuration would be more expensive than the current shallow-convection scenario. Rough calculations lead to an increased cost per simulation of 25–50 times, primarily due to the increase in resolution. Substantial savings could be had by using an even smaller domain, if deemed scientifically permissible. Additional savings could be achieved by not using any cloud scheme, but this would prohibit cases with small cloud amounts, which otherwise might be desirable to simulate. Limiting the LES ensemble size would also reduce cost, as would choosing a cheaper model than WRF to generate the LES.

C.3.5 Input Data such as Initial, Forcing, and Boundary Conditions

Input data for the model consist of the initial conditions, large-scale forcing profiles, and surface fluxes. Initial conditions are best taken from an ARM radiosonde profile, with the primary decision being the time of day to choose. Given that the turbulence decay at the end of the day and subsequent boundary-layer behavior is of primary interest, using the mid-day sounding would be appropriate. The model would then be integrated forward using the ensemble of large-scale forcings similarly to what is done for the shallow-convection scenario. An integration period of 18– 20 hours would permit spin-up of the daytime turbulent boundary layer, decay of the boundary layer, the nighttime stable conditions, and growth of the boundary layer the next morning. Observation-derived surface fluxes would be obtained from the Variational Analysis product, which smartly averages the observed fluxes around the SGP. The alternative of using an interactive soil model would be useful if one were to look at the role of the land in modulating the boundary layer, which would then require soil temperature and moisture profiles to initialize the model.

No additional instrumentation would be required at the SGP to accommodate the input requirements of the LES model.

C.3.6 Evaluation Data and Approach

Evaluation of the LES results for a clear-air scenario would focus on the turbulence details and overall structure of the boundary layer as it grows and decays. The Doppler lidars at the Central Facility and boundary facilities would be valuable for this along with the Raman lidar at the Central Facility. The boundary-layer top and wind characteristics would be retrieved from the multiple radar wind profilers around the facility combined with in situ wind, temperature, and humidity measurements from the 60-m tower.

Additional instrumentation that would enhance a clear-air LASSO scenario would be ways to measure and/or retrieve vertical fluxes of heat and moisture. Currently, vertical velocity variance can be estimated using the Doppler lidars. Combining the high-frequency vertical velocity measurements from the Doppler lidars with high-frequency profile measurements of temperature and moisture would, if done for similar sampling volumes, permit estimating vertical fluxes of energy and moisture. An instrument that could be considered for the moisture is a micropulse differential absorption lidar. Obtaining sufficient temporal resolution for temperature may be difficult.

C.3.7 Potential Issues and Proposed Mitigations

The primary difficulties for this scenario are accurately simulating the boundary-layer transition periods combined with balancing the cost of the resolution needed to accurately represent the nighttime stable conditions.

Accurately simulating the transition timing will strongly depend on obtaining accurate surface fluxes and large-scale forcings to drive the LES. Prescribing observation-derived surface fluxes will likely provide the best possible information for the surface boundary condition. The primary issue with the fluxes is determining their representativeness across the region since the LES domain represents a regional average and does not contain any surface heterogeneity. Alternatively, if an interactive soil model is used, initialization of the soil will be important and regional variability will need to be considered. The uncertainty in the large-scale forcings will be handled by running an ensemble of LES based on using the large-scale forcing ensemble developed for the shallow-convection scenario.

Simulating the stable boundary layer at night requires higher resolution than currently used for shallow convection, and thus will increase the cost of the simulations compared to the current LASSO shallow-convection configuration. This will be partially compensated for by using a short model top and not extending the domain to the tropopause. However, the stretched domain used above the mid-troposphere limits the benefit of this approach to some extent.

Additionally, we must accept the technical limitation of LES abilities to represent stable conditions. As noted in the description of the physics configuration, this can be partially alleviated by using a dynamic SGS approach, but that also increases the cost of the simulation.

The presence of low-level jets at the SGP is a complicating factor making the site not completely representative of generic stable conditions. Other areas in the world experience low-level jets, but their characteristics and frequency vary by location. The formation of the jet is a multiscale process involving the evening decay of turbulence, the subsequent decoupling of the surface from the lower troposphere, and the gently sloping terrain. This happens on spatial scales relevant to the geostrophic wind balance, and thus larger than the LES domain size. So, even though the turbulence, or transition to the lack thereof, is critical to the presence of the jet, the small-scale eddies within the LES domain will not be able to act properly to establish the jet in the LES domain unless it is very large. Thus, we will need to investigate the simulated jet behavior when the larger-scale jet behavior is imposed via the large-scale forcing with periodic boundaries, potentially contributing to double counting of some jet-related processes, versus how a nested domain would more naturally enable jet-related processes.

C.4 Arctic Cloud Scenario White Paper

LASSO Expansion Scenario

A Case for Arctic LASSO

A White Paper Submitted to the Atmospheric Radiation Measurement User Facility

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C.4.1 Short Description

This white paper outlines the case for an Arctic LASSO scenario. This scenario focuses on the upcoming Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) campaign. In addition, LASSO activities at ARM's NSA site are proposed to provide additional historical context. This combined LASSO effort would leverage significant ARM investment in observational infrastructure and would integrate nicely into a variety of international projects and activities.

C.4.2 Science Drivers

Recent observations reveal significant evidence of a rapidly-evolving arctic climate (e.g., Bekryaev et al. 2010; Hansen et al. 2010). Most notably, the lower arctic atmosphere has warmed at a rate nearly double that of the rest of the planet (Screen and Simmonds 2010), resulting in large changes to sea ice (e.g., Kwok and Untersteiner 2011). The changes in sea-ice and snow cover result in substantial modification to the earth's energy budget, with the underlying ocean and land being significantly darker and less reflective than the ice and snow surfaces they replace. Several recent studies (e.g., Stroeve et al. 2007, 2012) have highlighted the inability of climate models to correctly capture decadal sea ice decline as it has been observed, and this separation from reality, along with substantial variability between model predictions on the future of sea ice and other arctic features, may reduce confidence in model estimations of future global climate (Solomon et al. 2007). Yet we currently rely on these global models to inform our understanding of arctic amplification and other critical climate processes (e.g., Stuecker et al. 2018; Dai et al. 2019; Dethloff et al. 2018).

Arctic warming has been directly observed in long-term records along the North Slope of Alaska, adjacent to the western Arctic Ocean. Here, changes to permafrost depth and extent (Romanovsky et al. 2002; Rowland et al. 2010), modification of habitats (Burek et al. 2008), snow cover extent (Chen et al. 2016), and plant ecosystems (Sturm et al. 2001) have also been observed, and interannual variability in these variables are correlated, highlighting the interdependency of the system (Cox et al. 2017).

To fully evaluate connections between human activity and observed changes in arctic climate, as well as the long-term viability and safety of commercial operations at high latitudes, accurate weather and climate forecasts are critical (e.g., Kattsov et al. 2005; Walsh et al. 2002). Improving the quality of these forecasts requires that we improve the performance of models covering a variety of temporal and spatial scales. To meet this goal, we must address substantial uncertainties related to numerical simulations resulting from incomplete understanding of atmospheric phenomena and an inability to accurately reproduce key physical processes using the parameterizations employed. Improving model accuracy requires advancement of the simulation of several key atmospheric quantities. Global circulation features spanning the tropics and mid-latitudes can impact arctic climate. For instance, teleconnections between major convective events from Asian monsoons impact arctic sea ice extent (e.g., Grunseich and Wang 2016). Additionally, the local processes having significant controlling influence on the terms of the high-atitude surface energy budget (SEB) are typically directly impacted by larger-scale dynamic intrusions (Pithan et al. 2018). The primary terms governing this budget include solar ("shortwave") and terrestrial ("longwave") radiation reaching the surface, surface reflectivity, surface temperature, turbulent fluxes of heat, sub-surface heat conduction, and surface phase transitions. The SEB energetically couples the atmosphere and surface, thereby playing a central role in governing arctic weather and climate.

Unfortunately, some atmospheric phenomena most critical for accurate simulation of the SEB are also among the least-constrained. One example is the challenge associated with the simulation of arctic cloud and aerosol properties, and the interactions between them (e.g., Solomon et al. 2007; Tjernström et al. 2008; de Boer et al. 2012, 2014; Wesslén et al. 2014; Sotiropoulou et al. 2016; Solomon et al. 2018). Measurements of cloud phase reveal the frequent occurrence of cloud liquid. When coupled with measurements of radiation at the surface, these cloud measurements have demonstrated that cloud phase, and particularly this presence of supercooled liquid water, strongly impacts the net radiative effect of clouds (Sun and Shine 1994; Shupe and Intrieri 2004; Sedlar et al. 2011; Persson et al. 2017; Turner et al. 2018). Additionally, surface- and space-born sensors have shown that clouds are frequent in all seasons across the Arctic, and that liquid cloud water occurs 30–60% annually, ~20% of the time in winter, and regionally up to 80% of the time in late summer (e.g., Wang and Key 2005; Shupe 2011; Cesana et al. 2012; Kay and L'Ecuyer 2013). Clouds have, on an annual basis, a net warming effect on the arctic surface (Curry and Ebert 1992) and warm the surface in all seasons except mid-summer (Intrieri et al. 2002; Dong et al. 2010). However, the timing of transitions between net cloud warming or cooling states involve complex interactions among a number of surface and atmospheric variables (e.g., Sedlar et al. 2011; Cox et al. 2016).

This seasonally dependent impact of clouds makes estimates of radiative forcing under climate change scenarios unclear and highlights the need to be able to accurately simulate clouds and the underlying environment across a range of seasons and conditions. Climate-induced changes to clouds leading to stronger radiative forcing in summer act to cool the surface, while similar changes in autumn would result in surface warming. These scenarios have different impacts on annual ice formation, which in turn changes arctic moisture dynamics that feed back onto cloud systems. Importantly, the net radiative effect of clouds is also determined by the sun angle and local surface albedo, which control the degree to which shortwave effects offset longwave effects (Shupe and Intrieri 2004). Therefore, seasonal changes to the arctic surface state directly modify cloud radiative forcing, even without any associated changes to the clouds themselves. Through these radiative processes and others, clouds are expected to play important roles in arctic climate feedbacks (Winton 2006; Kay and Gettelman 2009).

The simulation of atmospheric boundary layer (ABL) structure is also important. Linking the free troposphere and surface, this layer controls interaction between synoptic influences and the SEB. It also has a controlling influence on (and is controlled by) the presence of clouds. As a result of frequent warm advection aloft and strong radiative surface cooling, the arctic ABL can often be very stably stratified (e.g., Persson et al. 2002; Tjernström and Graversen 2009; Tjernström et al. 2015; Persson and Vihma 2017). In contrast to farther south, stably stratified conditions in the Arctic can be very long-lived. On the other hand, when clouds, sunlight, and/or strong winds are present, the ABL can become much less stable through a combination of radiative and dynamical processes (e.g., Tjernström and Graversen 2009; Brooks et al. 2017). Therefore, processes related to the governance of ABL structure directly impact the SEB through their controls on the sign and magnitude of surface turbulent fluxes and through other means. As hinted above, the processes related to ABL structure are strongly linked to the presence of cloud, through a series of two-way interactions. Not only can the structure of the ABL influence the formation, persistence, and properties of the clouds, but conversely the presence of clouds results in modulation of the ABL structure (e.g., Miller et al. 2013; Shupe et al. 2013; Sedlar and Shupe 2014; Sotiropoulou et al. 2014).

Given this, errors in the representation of ABL structure, arctic clouds, and the physical processes supporting them in numerical models can result in incorrect simulation of surface radiative fluxes at high latitudes (e.g., Tjernström et al. 2008; de Boer et al. 2012; Sotiropoulou et al. 2016). Such errors lead to uncertainty in numerical forecasts of weather and climate, in part through the profound impacts on the simulation of further melting or growth of surface snow and ice (Kwok and Untersteiner 2011; Kay et al. 2008). A variety of studies (e.g., Klein et al. 2009; Morrison et al. 2011; de Boer et al. 2012; Wesslén et al. 2014; Eisenman et al. 2007; Solomon et al. 2009; Karlson and Svensson 2011, 2013; Sotiropoulou et al. 2016) have illustrated significant issues regarding the correct simulation of cloud and cloud phase in models of various scales. Intermodel variation in liquid water path (LWP) and cloud phase partitioning can be substantial (Karlsson and Svensson

2013), leading to variability across models of 10s of W m^{-2} for the overall cloud radiative effect on the surface (Lenaerts et al. 2017). Models can also misrepresent the annual variability of clouds (Cesana and Chepfer 2012), underestimating liquid water occurrence in low-level clouds during non-summer months (Cesana et al. 2012, de Boer et al. 2012), and fail to produce the appropriate amount of cloud liquid water at cold temperatures (Liu et al. 2011; Barton et al. 2012). Even in the simulation of cloud fraction, the spread between CMIP5 models did not decrease relative to CMIP3 models (Karlsson and Svensson 2013), suggesting that only limited progress is being made in tackling known arctic cloud modeling deficiencies.

The interplay among clouds, boundary-layer structure, and surface processes is captured nicely in Morrison et al. (2012). This paper discusses the prevalence of two radiative states at high latitudes first reported by Stramler et al. (2011). The “radiatively clear” state (~-40 W m^{-2} net surface longwave radiation) includes cloud-free and thin cloud conditions, and often features a stably-stratified near-surface atmosphere. Conversely the “radiatively cloudy” (~0 W m^{-2} net surface longwave radiation) state generally results from conditions dominated by liquid-containing clouds. In principle, these radiation values agree with surface longwave radiation estimated by models under the clear and cloudy conditions described. Where models struggle, however, is in correctly predicting when a given state should be present, and how to transition from one of these states to the other. This state selection is controlled in part by the ABL structure and its evolution around the time of cloud occurrence. The evolution of the lower atmosphere in response to surface forcing, advection, and cloud processes represents a central control on surface energy budget.

Several studies (e.g., Tjernström et al. 2004a, b, 2005; Dethloff et al. 2003) have shown substantial sensitivity of model results to the boundary- and surface-layer parameterizations chosen to represent the arctic environment. This selection can impact surface turbulent heat fluxes, and thereby the near-surface temperature. A significant challenge for the models includes adequate representation of the stable boundary layer. Large-scale advection of southerly air and strong radiative cooling of the near-surface environment through a cold, dry atmosphere simultaneously work to stabilize the arctic boundary layer. This stratification can be very significant, with temperatures warming 10–20 C in the lowest few hundred meters. These stable boundary layers have been evaluated in a variety of model-based studies (e.g., Steeneveld et al.,2006; Tjernström et al. 2004b; Delage 1974, 1997; Nieuwstadt and Driedonks 1979; Kosovic and Curry 2000) and a limited number of observational efforts (e.g., ,Kahl 1990; Grachev et al. 2005, 2007; van den Kroonenberg and Bange 2007). These studies have demonstrated that the parameterization schemes currently in use in weather and climate models are using turbulence closure schemes that are often too diffusive to handle these strongly stratified layers. The result is inadequate representation of these stable conditions and biases in near-surface temperature and surface energy exchange.

In addition to the stably stratified boundary layer, there are also various forms of well-mixed states that can occur in the lower atmosphere. These can be surface-driven convective layers, resulting from diurnal heating of land surfaces by the sun or by the advection of cold air over warmer (e.g., open water) surfaces. Specifically, leads in the polar ice pack, which range in scale from a few meters to several kilometers (Marcq and Weiss 2012) can impart significant influence on the vertical exchange of energy. This is because extreme air-water temperature contrasts in winter (20–40°C) support turbulent heat fluxes over leads that can be orders of magnitude larger than over thick ice (Maykut 1982, 1986; Andreas and Murphy 1986). For example, Andreas et al. (1979) measured sensible and latent turbulent heat fluxes exceeding 400 W m^{-2} and 130 W m^{-2}, respectively, above open leads during winter. Such leads can result in the generation of cloud decks, which can significantly alter the surface infrared (IR) radiation budget (Curry et al. 1993). For example, Pinto and Curry (1995) calculated that lead-induced cloudiness increases the downwelling IR flux at the surface by up to 70 W m^{-2}. Observations during the SHEBA (Surface Heat Budget of the Arctic Ocean) experiment show that low clouds in winter can increase the downwelling IR flux by as much as 100 W m^{-2} (Intrieri et al. 2002). Additionally, well-mixed states can be driven by stratiform cloud decks themselves, which feature strong cloud-top cooling, resulting in destabilization of the cloud-top environment and density-driven eddy generation. Both the surface-driven and cloud-driven convection have proven challenging to our modeling capabilities, with the latter struggles caused in large part by problems with the simulation of liquid-containing clouds across the cold arctic atmosphere (e.g., Klein et al. 2009).

A significant source of the problems related to the simulation of liquid-containing clouds is excessive ice production in cold conditions. This excessive production of ice results in unwarranted removal of water vapor through ice depositional growth processes and the Wegener-Bergeron-Findeisen (WBF) mechanism (Wegener, 1911; Bergeron, 1935; Findeisen, 1938). This ultimately results in excessive evaporation of liquid water and over-simulation of the radiatively clear state (e.g., Prenni et al. 2007). However, the primary causes of excessive ice production are not well understood. Besides the unclear role of entrainment and associated length scales, the initial formation of ice crystals in the atmosphere plays a central role in this problem. This process, which largely centers on the availability of ice nucleating particles (INPs), has been identified as a critical gap in our modeling ability and as being connected to some significant model radiation and precipitation biases at mid- and high latitudes. The ability of particles to serve as INP depends on composition (i.e., chemical, mineral, or biological makeup), morphology, and size, and therefore indirectly on source and transport pathway. INPs nucleate ice through mechanisms that are a combined function of temperature, saturation with respect to ice, and INP size and composition (Hoose and Möhler 2012). Correctly parameterizing the complex interplay between governing processes has been shown to be challenging (e.g., Klein et al. 2009; Morrison et al. 2011).

In addition to ice nucleation, uncertainty arises from the handling of ice crystal shapes in numerical models. Because the aspect ratio between dimensions of individual ice crystals govern the rate at which these crystals grow (e.g., Kuroda and Lacmann 1982; Chen and Lamb 1994; Fukuta and Takahashi 1999) and fall through the atmosphere, incorrect simulation of particle shape can result in the under- or overestimation of the removal of water vapor from an atmospheric layer. This in turn has a substantial impact on cloud lifetime (Pinto 1998; Harrington et al. 1999; Morrison et al. 2005) and thereby on surface radiative forcing. Studies of spherical ice by Korolev and Isaac (2003) and Korolev and Field (2008) provide a common basis for understanding the complex interplay between ice crystal properties and liquid water in mixed-phase clouds. For completely understanding this balance, information on both ice crystal number and ice crystal shape are critical. Sulia and Harrington (2011) quantified the sensitivity of mixed-phase cloud phase partitioning to ice crystal aspect ratio and effective density using a parcel model and parameterizations rooted in laboratory data. They found significant sensitivity of the liquid glaciation rate to the evolution of particle aspect ratios and effective density. Spherical crystals resulted in an under-prediction of glaciation rates for typical ranges of ice crystal concentrations (between 1–100 L^{-1}). Because of these sensitivities, it is important that weather and climate models accurately parameterize the evolution of ice crystal aspect ratio and effective density.

One of the reasons why model performance at high latitudes has been challenging to evaluate and improve is that the Arctic represents a relatively inaccessible region where it is difficult to make reliable measurements over extended time scales. Yet, exceptions to this generalization exist, and DOE has substantially contributed to the collection of such data sets. For example, the ARM facility (Verlinde et al. 2007, 2016; de Boer et al. 2018, 2019) has committed significant resources towards collecting data through long-term observatories (North Slope of Alaska, Oliktok Point) and a variety of recent and future field campaigns (e.g., MOSAiC, Profiling at Oliktok Point to Enhance YOPP Experiments [POPEYE], Aerial Assessment of Liquid in Clouds at Oliktok [AALCO], Mixed-Phase Arctic Cloud Experiment [M-PACE], Indirect and Semi-Direct Aerosol Campaign [ISDAC], Cold-Air Outbreaks in the Marine Boundary Layer Experiment]COMBLE[2]). Measurements coming from such deployments help to improve data availability and support broader international activities such as the Year of Polar Prediction (YOPP) and the International Arctic Systems for Observing the Atmosphere (IASOA). In combination with existing remote-sensing data sets, such observatories provide information critical to model development and improvement.

Finally, it is important to note that several international efforts are currently focused on improved simulation of the arctic environment, and all of these activities can benefit from detailed simulations of particular phenomena of interest. Some of these efforts could be of great help to an arctic LASSO in terms of improving forcing data sets, providing observational means for model evaluation, and offering additional modeling activities with which to integrate and couple our efforts. Included are:

- *The Year of Polar Prediction (YOPP):* The YOPP is a central activity for the World Meteorological Organization's Polar Prediction Project (WMO PPP). During this period, the WMO is coordinating a period of intensive observing, modelling, verification, user-engagement, and education activities. Such activities could be of significant benefit to ARM for the implementation and evaluation of arctic LASSO simulations.
- *Ongoing evaluation of operational NOAA numerical weather prediction (NWP) models (RAP/HRRR-AK):* The 13-km Rapid Refresh (RAP) and 3-km High-Resolution Rapid Refresh (HRRR) models (Benjamin et al. 2016) are run operationally by the National Weather Service

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[2] MOSAiC: Multidisciplinary drifting Observatory for the Study of Arctic Climate
POPEYE: Profiling at Oliktok Point to Enhance YOPP Experiments
AALCO: Aerial Assessment of Liquid in Cloud at Oliktok
M-PACE: Mixed-Phase Arctic Clouds Experiment
ISDAC: Indirect and Semi-Direct Aerosol Campaign
COMBLE: Cold-Air Outbreaks in the Marine Boundary Layer Experiment

and provide critical forecast guidance for the aviation and severe weather communities. These models are initialized hourly using all available input data, and perform 18- to 39-hour forecasts, depending on the initialization time. Neither model has been validated in the Arctic, yet both are used to provide guidance to the Federal Aviation Administration and other agencies. Nonetheless, due to the volume of data assimilated by the RAP and HRRR-Alaska, the analyses produced by these models may be good options for forcing regional scale and LES models.

- *MOSAiC observational and modeling efforts:* MOSAiC represents a unique opportunity to capture detailed measurements in the central Arctic Ocean, as required to run LES. These measurements can be used for model forcing and evaluation. Additionally, the wealth of modeling activities (particularly with regional and climate models) related to MOSAiC should offer a direct interface with the rest of the global modeling community and instantly introduce a group of users for these simulations.
- *DOE HiLAT-RASM project:* One of the goals of High-Latitude Application and Testing of Earth System Models-Regional Arctic System Model (HiLAT-RASM) project is to understand the role of fine-scale transport of climatically important constituents (e.g., aerosols, moisture, heat) in affecting arctic clouds, precipitation, surface albedo, and energy budget using DOE-sponsored global and regional climate models (i.e., E3SM, CESM, RASM/WRF) at a variety of model resolutions. With atmospheric model grids down to 3 km in the Arctic, it is still challenging to perform process-level model evaluation using existing sporadic measurements. A routine LES campaign like LASSO, combined with the MOSAiC field campaign and/or ARM site measurements, would be very helpful in identifying and attributing biases in the current-generation climate models and guiding the development of future-generation cloud-permitting E3SM, particularly, for understanding the complex arctic climate system.
- *E3SM development:* The E3SM model has a vision for its v3/v4 development to push for non-hydrostatic, vertical-velocity-resolving global resolutions at sub-4 kilometers. A primary objective of this development is to improve understanding of low-cloud feedback and convection. The data- sparse area of the Arctic would provide a data set used for the next decade to constrain and validate E3SM development.
- *Polar-CORDEX:* Polar-Coordinated Regional Downscaling Experiment – Arctic and Antarctic Domains (CORDEX) is an internationally coordinated experiment in which regional climate models are forced with common lateral and surface boundary conditions. The pan-Arctic model domain simulations then provide a unique test bed to evaluate the influence of model resolution and physical parameterization schemes on the time evolution of the arctic atmosphere and SEB. Currently, a Polar-CORDEX study has commenced where a suite of six regional climate models have simulated the Arctic Clouds during Summer Experiment (ACSE, Tjernström et al. 2015; Sotiropoulou et al. 2016) during July–October 2014. Observations of energy fluxes and cloud macrophysical properties from ACSE have been examined against the model simulations to identify inter-connected biases in clouds, radiation, and ultimately the SEB. The ACSE and regional climate model intercomparison experiment has served as “test case” for a coordinated regional climate model experiment for the MOSAiC central observatory.

- *(AC)³:* During phase II of the European Arctic Amplification: Climate Relevant Atmospheric and SurfaCe Processes and Feedback Mechanisms (AC)³ project, there are plans for a contingent to conduct daily Lagrangian LES for the *Polarstern*, throughout the MOSAiC drift period. These simulations will build on experience gained with setting up LES for days observed during the Physical Feedbacks of Arctic Planetary Boundary Level Sea Ice, Cloud and Aerosol (PASCAL) field campaign (June 2017), which were used to test some ideas. This Lagrangian approach will offer additional insight that can complement possible Eulerian MOSAiC LASSO experiments.
- *Development of the Coupled Arctic Forecasting System (CAFS):* The NOAA/Cooperative Institute for Research in Environmental Sciences (CIRES) Coupled Arctic Forecast System (CAFS) is a high-resolution fully-coupled model of the Arctic Ocean and surrounding coastal regions. 10-day forecasts of the arctic climate system are produced daily and used by the National Weather Service and scientific campaigns as model forecast guidance and by NOAA/CIRES to identify biases that limit the skill of the forecasts due to inadequate representation of physical processes. Of specific interest is the inability of microphysical schemes to simulate the annual cycle of cloud ice and liquid water in the Arctic to first order due to inadequate parameterization of ice nucleating particles and the inability to maintain cloud liquid in the presence of cloud ice. An arctic LASSO will be an optimal testbed to improve microphysical schemes currently used in CAFS and other arctic simulations.

Here, we outline plans to leverage these observational assets and routine high-resolution simulations completed under the LASSO umbrella to support the ongoing model improvement efforts listed above in advancing our current ability to simulate the lower arctic environment. The sections below provide additional details on how these modeling activities should be carried out, the benefits of doing so, and possible challenges associated with these ideas.

C.4.3 Full Description

While there are several options for an arctic LASSO implementation, we are currently afforded a “once in a lifetime” opportunity to have sufficient observational information in the central Arctic Ocean to drive and evaluate detailed numerical simulations of this environment. There is a general paucity of observations from over the Arctic Ocean. Most such observations are taken during only brief periods in summer (e.g., Tjernström et al. 2012) and a full annual cycle has not been observed since SHEBA (Surface Heat Budget of the Arctic Ocean, Uttal et al. 2002) in 1997–98. The upcoming MOSAiC campaign will provide unprecedented and not-soon-to-be repeated perspectives on the coupled arctic climate system. The extensive instrumentation to be deployed for MOSAiC will offer detailed insight into the vertical and horizontal heterogeneity of atmospheric properties and, importantly, the underlying surface. At the same time, this suite of instruments offers various levels of redundancy to minimize data gaps due to instrument failure and environmental impacts. When it comes to high-resolution simulations, the central arctic region has received substantially less attention than the Barrow/Beaufort area, where model intercomparisons have been completed for the SHEBA, M-PACE and ISDAC campaigns. Additionally, the quasi-uniform ice surface offers, in many ways, a simpler lower boundary condition than present at the NSA and Oliktok (OLI) sites, where the coastal gradient can pose significant challenges for limited-area models. As such, we prescribe a scenario that would result in the generation of high-resolution LES to help understand key atmospheric processes as described above for the climatically sensitive central Arctic Ocean, and the ability of existing parameterizations to reproduce these conditions.

As outlined above, this scenario should target cases for which large-scale models struggle. Specifically, cases with stratiform clouds as well as clear cases supporting the development of stable boundary layers should be included. The maintenance and evolution of the arctic inversion and large-scale transport of water vapor are thought to play central roles in governing atmospheric radiative state, and thereby have significant influence on the phenomena listed. These phenomena may occur under relatively quiescent synoptic forcing, with the ultimate state selection resulting from the availability of moisture. Therefore, simulations could focus on cases under relatively stable synoptic regimes offering a clean break between the influence of the larger-scale flow, which can be included as mean tendencies, and the local scale. These cases could potentially be identified through the use of self-organizing maps (SOMs) or other classification schemes. Completing simulations for a suite of similar synoptic states should result in a distribution of biases and help to highlight model strengths and weaknesses in simulating a given condition. The classification scheme should be broad enough to allow for the execution of a statistically-relevant set of simulations.

Ultimately a LES configuration offers the necessary, detailed insight into turbulence, radiation, and their interaction with microphysics that cannot be captured in lower-resolution simulations. Detailed representation of such processes is critical for understanding TKE production under different atmospheric states, the budgets of heat, moisture, momentum, and aerosols associated with stratiform cloud conditions, sensitivity of cloud life cycle to surface coupling state and precipitation, cloud-top entrainment, representation of temperature fronts in stable layers, cloud phase, and more. Additionally, LES can provide statistical distributions of key quantities on the sub-climate-model grid scale. Such distributions can be useful for climate model development and benchmarking. Below we provide details on the proposed configuration of these LES, including information on forcing and evaluation data sets.

C.4.4 Model Configuration

As a primary setup for MOSAiC LASSO simulations, we propose an Eulerian grid around the MOSAiC ship that moves with the drift. This grid should have sufficient resolution to capture fine details related to both clear (stable) and cloudy environments. For the latter, the cloud-top region is of particular importance as entrainment processes and the structure of the cloud-top inversion impart significant influence on cloud processes and lifetime.

To capture the required scales, we recommend a horizontal extent of 30x30x4 km. This scale would capture a variety of eddy scales and allow for the simulation of some horizontal heterogeneity within the domain. Such a domain should have periodic boundary conditions to allow for the development of a mature turbulent state. While periodic boundary conditions would work well for many environmental conditions, it would be problematic for surface heterogeneities (depending on their extent).

Conversely, a simulation at this scale would not capture some potentially important mesoscale features or the influence of surface heterogeneities. However, there are a substantial number of other modeling activities that are planned for the MOSAiC drift, including operational forecasting activities leveraging a variety of fully coupled and atmosphere-only mesoscale models. Therefore, for scientific purposes it is possible that information on mesoscale influences on the observed conditions could be derived from these external simulations. Additionally, the idea of nesting the Eulerian LES inside one of these mesoscale models or allowing for time-varying forcing to align with evolving conditions may help to capture some of the influences of these mesoscale effects and provide an ability to handle inhomogeneous surface conditions that may impact the observed condition at the ship. An example of this would be a nearby lead in the sea ice that could impact clouds and atmospheric state locally but might not be captured by an LES. In the case of a nested LES, an elongated grid would be required in order to spin up fine-scale turbulence before reaching the MOSAiC ship position.

The horizontal resolution for these simulations would ideally be on the order of 20–40 m to capture fine-scale turbulent structures associated with shallow clouds and to enhance representation of the limited turbulent features contributing to mixing in the stable boundary layer. However, we recognize that this may be challenging computationally and therefore advocate for a maximum resolution of 50 m horizontally. Vertically, the model would ideally feature a very high (10 m or finer) resolution through the depth of the cloud-top inversion and/or other stable regions (e.g., stable boundary layer). However, given that the level of user input necessary to adjust simulation structure for individual cases is likely challenging for an operational setup such as required for LASSO, a pre-determined variable vertical grid spacing could also work. The nature of the features being simulated might require this variable grid to be defined by the conditions being simulated — for example, fine (10 m) resolution over altitude regions that are either statically stable or interacting with those stable layers, and coarser (30 m) in other portions of the lower atmosphere. Fortunately, the arctic "lower" atmosphere is generally shallower (~1–1.5 km) than in other parts of the world, allowing for more of the grid to be run at a coarser resolution. Above the lower atmosphere, a vertical resolution stretching to 50 m should be sufficient.

Beyond the general configuration of the model grid, there are some specific considerations for model physics as well. Of greatest concern is the use of a microphysical scheme capable of handling, at least at some level, mixed-phase cloud conditions. Previous simulations have demonstrated that this means employing a double-moment microphysics scheme (e.g., Morrison and Gettelman 2008). Additionally, the past decade or so has seen the development of a new paradigm of microphysical parameterization. These parameterizations attempt to simulate the evolution of ice particle properties (such as aspect ratio, effective density, rime fraction) with time instead of using pre-defined classes as is typical of traditional schemes (e.g., Chen and Lamb 1999; Hashino and Tripoli 2007; Morrison and Grabowski 2008; Jensen et al. 2017). However, the extent to which such parameterizations accurately portray the state of arctic clouds has only been tested in a very limited manner. If feasible from a computational expense perspective, integration of ice particle property microphysical schemes, either in a bin (e.g., Hashino and Tripoli 2007, 2008, 2011a, 2011b; Fan et al. 2009) or bulk form (e.g., Morrison and Milbrandt 2015; Jensen et al. 2017) should be considered. In some ways, it would be very nice to be able to run an ensemble of sorts for cases of interest that includes the same general model setup and forcing, but varies the microphysics used to evaluate sensitivity to this critical model component.

In addition to the microphysics, care should be taken to implement appropriate parameterizations governing mixing and turbulence. This would include thorough evaluation of the boundary-layer and surface-layer parameterizations employed. If time and resources permitted, a sensitivity study with low- to high-order closure schemes may help illuminate the sources of model uncertainties related to these schemes. For example, a comparison between the Deardorff, Smagorinsky, CLUBB (Golaz et al. 2002), and simplified higher-order closure (SHOC) schemes and their ability to accurately reproduce the mixing state of a variety of arctic atmospheric conditions would help to better understand the influence of such parameterizations.

Finally, there should be considerations for the appropriate length of arctic LASSO simulations. Unlike at SGP, where simulation length is governed by the diurnal cycle, in the Arctic, the diurnal cycle is subdued, and different time scales are likely to take priority. For example, the time required to appropriately spin up turbulence and cloud ice properties should be considered. Similarly, advective timescales should be influential in determining an appropriate simulation length, given the reduced influence of the solar cycle. At the same time, the extended polar night and day may simplify an idealistic simulation by allowing for a weak (or non-existent) solar forcing.

C.4.5 Input Data such as Initial, Forcing, and Boundary Conditions

The initial conditions for a MOSAiC LASSO implementation could be challenging due to the remote location of the MOSAiC experiment and inability to deploy an extensive spatial observing network as has been done at SGP. Having said that, similar efforts have been undertaken before (e.g., routine SCM for SHEBA). Also, MOSAiC LASSO simulations should benefit from the extensive observing and modeling work that is associated with this project. Additionally, given the connection to YOPP and planned intercomparison of regional climate model simulations within Polar-CORDEX, there should be additional model runs and analyses to help support the establishment of such conditions, as well as extra observations (e.g., radiosondes) to improve their quality. Below, we outline a strategy for providing the necessary conditions for routine simulations.

For initial conditions, we recommend using a hybrid approach leveraging both observations and model output. Specifically, thermodynamic and wind profiles should be pulled from the data obtained at the ship. The most direct sources for this information are the 4x daily radiosondes that will be launched. It may also be possible to incorporate wind data from the radar wind profiler or other remote sensors. Additionally, surface meteorological measurements should be of good quality and can help to constrain the near-surface environment over time. Location should be flexible and follow the coordinates of the ship throughout the cruise. In addition to these conditions, estimates of the large-scale vertical velocity (omega) and horizontal temperature and water vapor advection should be provided, and are probably best provided by global model output (e.g., ERA-5 or ECMWF operational analyses). Given the potential for uncertainty related to this large-scale forcing, it may make sense to introduce several ensemble members that include a variety of large-scale forcing terms, as determined by different members from the ERA-5 ensemble. The lower boundary condition should be assigned based on evaluation of local measurements of surface albedo, open water fraction, ice/water temperature, turbulent surface fluxes, and possibly surface roughness. It may be necessary to further analyze the homogeneity of the surface state using satellite data products, paying particular attention to areas of open water in the nearby environment, as this could produce a significant source of heat and moisture. These terms may be time-varying (particularly the surface fluxes).

In addition, aerosol properties should be assigned. Perhaps one of the biggest questions is whether these should be assigned based on available surface/in situ measurements, or whether there should be an ensemble of LES runs that try to account for uncertainty in aerosol properties. This is particularly true for ice nucleating particle concentrations, to which simulations are very sensitive, but where we have very little information to help constrain the simulation configuration. For some specific cases, there may be some relief with respect to knowing more about the aerosol properties, as there are plans to sample aerosols using tethered balloons. Looking beyond aerosol properties, it will also be important to assign spectrally resolved downwelling radiation terms at the top of the domain. In the past, these terms have been generated using a combination of remote-sensing measurements and radiative transfer simulations (e.g., using the Rapid Radiative Transfer Model [RRTM], Clough et al. 2005).

C.4.6 Evaluation Data and Approach

As mentioned, MOSAiC will offer by far the most comprehensive suite of environmental observations ever collected in the central Arctic. Many of these observations will be very useful for evaluation of LASSO simulations. Interestingly, there are numerous opportunities for evaluating spatial gradients, both locally (unmanned aerial systems [UAS], central observatory network) and further away (distributed network, manned aircraft, satellites). Additionally, planned manned aircraft missions should offer some opportunities to get detailed cloud microphysics measurements that could be used for evaluation across the entire model domain. Below we provide a table of instruments and key quantities, separated by general area, that should be used for evaluation of the simulations.

Table 8. A summary of observations at MOSAiC that can be leveraged for simulation evaluation. Quantities designated with a * are not continuous.

Measurement Area	Instrument	Key Quantities	Operator (ARM/Other)
Thermodynamic State			
	Radiosondes (4x daily)	T, q, p	Both
	UAS*	T, q, p	Other
	Tethered Balloon*	T, q, p	Other
	AERI	T, q	ARM
Turbulence/Dynamics			
	Doppler Lidar	u, v, w, eddy dissipation rate, variance, skewness	ARM
	KAZR	w, eddy dissipation rate	ARM
	UAS*	w, TKE, eddy dissipation rate	Other
	TBS*	w, TKE, eddy dissipation rate	Other
	RWP	u, v, w	ARM
	Manned aircraft*	u, v, w	Other
Cloud Physics			
	KAZR	IWC, IWP, w, Doppler spectra, cloud-top height, precipitation rate	ARM
	HSRL	Re, N, water content (with KAZR)	ARM
	Manned Aircraft*	IWC, LWC, Re, N_{liq}, N_{ice},	Other
	SACR	Aspect Ratio,	ARM
	MWR	LWC	ARM
	AERI	LWC, Re, Nliq	ARM
	MPL/Ceilometer	Cloud base	ARM
	Weighing gauge	Precipitation rate	ARM
	Optical snowfall sensor	Snow particle type, size distributions	Other
Surface Energy Budget			
	Ground/Sky Radiometers	LW SW irradiances	ARM
	ECOR / Flux stations	Turbulent fluxes	Both
	UAS*	Turbulent fluxes, albedo	Other
	TBS*	Column irradiances / albedo	Other

C.4.7 Potential Issues and Proposed Mitigations

The plan outlined here has a few potential challenges. Among the most significant are the possible impacts of a heterogeneous surface, the uncertainty associated with aerosol properties, impacts of errors in the large-scale forcing, and the known challenges associated with accurate representation of ice microphysics. For the spatial heterogeneity issue, this is a significant problem if surface features occur in a non-uniform manner (e.g., leads). These features will have a significant impact on the surface energy budget, thereby feeding back on thermodynamic and cloud properties downstream. This would be problematic with periodic boundary conditions, as those changes would be carried throughout the simulation, and amplified as the feature is revisited time after time. One possible solution would be to run a nested LES without periodic boundary conditions. This might come with its own set of issues, as discussed above, with respect to initial conditions for the simulation, but would allow for extending the number of cases that could be included and might result in progress related to interesting science questions about the impact of inhomogeneities on clouds and the boundary layer. Another possible solution would be to simply ignore the surface feature, though depending on its scale and properties, removing this influential source of energy would likely result in a mischaracterization of the atmosphere.

With regard to the aerosol issue, one possible solution that was mentioned earlier would be to run some sort of ensemble with varying aerosol conditions. A primary item to vary would be the ice nucleus concentration, though other aerosol properties could also be revised. However, this is a large phase space, and the number of different sensitivity studies could quickly grow to be an unsupportable configuration. The other solution would be to use the information available to define a size distribution relevant to the simulated atmospheric column. However, this approach would require significant manual intervention and would require the processing of aerosol data before simulations could be completed, likely enhancing the lag time.

This aerosol issue can have impacts on ice nucleation, though our understanding of how to parameterize this crucial process is limited. Because of this, current parameterizations regulating ice crystal number concentration rely more on tunable coefficients to produce the expected ice concentrations rather than on the actual aerosol properties. Thus, on a practical side, it is probably more important to know the target ice concentration than aerosol properties, and our knowledge of this for MOSAiC will generally be limited to what can be derived from remote-sensing retrievals. When it comes to issues beyond those related to ice nucleation (e.g., habits, spectral shape, etc.), a number of modeling studies with constrained ice concentration have demonstrated that these can also be very impactful on the simulated state (e.g., Avramov and Harrington 2010; Ovchinnikov et al. 2014). It is difficult to say how large of a challenge this poses to the simulation of a variety of cases.

Another possible issue is the accuracy of the large-scale forcing prescribed for these simulations. Small errors here could result in the simulations diverging from reality over time, due to excessive accumulation or depletion of key quantities, or errors associated with the large-scale vertical velocity. As an example, global models and/or reanalysis products are notorious in misrepresenting sharp inversion that are frequent in the Arctic. So, it is almost certain that the initial profiles will have to come from radiosondes. Even when the initial profiles are good, the profiles of large-scale advective tendencies may be smoothed and may therefore bias the profile evolution. As is done in the current LASSO, it is always wise to get these large-scale tendencies from multiple sources. Doing so allows for some characterization of uncertainty. It is possible that the large-scale forcing estimates from operational analyses are somewhat improved for MOSAiC due to the assimilation of additional measurements to be made during YOPP and at the ship itself. It is also possible to "reverse engineer" initial states in the model by adjusting biases in forcings derived from global models. Doing so makes use of the long memory of arctic air masses for upstream conditions. As mentioned above, we could implement an ensemble of forcing data sets, either from various global model products, or from the ensemble of solutions from a single product (e.g., ERA-5).

An additional challenge comes with the possibility of data outages on the ship. There may be breaks in the data collection related to large storms, major events, etc. In these instances, there may be gaps in the data sets supporting arctic LASSO, with limited options for data redundancy. Additionally, given the challenges associated with the remote location, it could be difficult to fix instrumentation in case of major failures. This could result in the unavailability of data sets required to force the simulations for extended time periods. This is challenging to protect against, though of course the hope is that any outages are of limited duration.

Finally, a possible challenge results from the duration of the MOSAiC campaign. The ship is scheduled to drift for essentially one full calendar year. While there is no doubt that several mixed-phase clouds and stable boundary layers will be observed over this year, it is not clear that these cases would span the range of possible conditions. Because of this, they may not cover the entire phase space as would be of interest to fully evaluate the parameterizations being used. This is particularly true when you consider the temporal variation of a combination of large-scale forcing conditions and aerosol properties. To account for this, we propose that NSA be used as a secondary site to provide additional historical context and expand the statistics of the cases sampled. While NSA comes with a variety of additional challenges, including the presence of the coastline, it is clear that this site has more observational coverage than the other arctic ARM sites. The configuration for this site may need to be adjusted to conform to the local conditions, but it is hoped that the initial simulations completed for the MOSAiC campaign would help to inform best practices for future NSA simulations.

C.4.8 References (Arctic Scenario)

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