U.S. DEPARTMENT OF ENERGY | Office of Science

DOE/SC-ARM-23-035

Science Plan for the Deployment of the Third ARM Mobile Facility to the Southeastern United States at the Bankhead National Forest, Alabama (AMF3 BNF)

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September 2023

ARM

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How to cite this document:

C Kuang, S Giangrande, S Serbin, G Elsaesser, P Gentine, T Heus, M Oue, J Peters, J Smith, A Steiner, A McComiskey, M Jensen, A Sedlacek, P Kollias, A Vogelmann, H Morrison, M Petters, D Turner, 2023. Science Plan for the Deployment of the Third ARM Mobile Facility to the Southeastern United States at the Bankhead National Forest, Alabama (AMF3 BNF). U.S. Department of Energy, Atmospheric Radiation Measurement user facility, Richland, Washington. DOE/SC-ARM-23-035.

Work supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Executive Summary

In 2018, the U.S. Department of Energy (DOE) held a workshop for the Atmospheric Radiation Measurement (ARM) (Mather and Voyles 2013) user facility to discuss critical climate challenges and locations where key ARM Mobile Facility (AMF) observational assets could impact Earth system modeling (ESM). As an outcome, the southeast United States (SE U.S.) was identified as a high-priority region to target climate-process studies that promote a deeper understanding of the climate system and bolster ARM interactions with the community to drive ESM advancement.

The DOE ARM user facility is a globally recognized leader in deploying and operating strategically located observation sites around the world for studying the properties of aerosols and clouds and their interaction with radiation, precipitation, and the Earth's surface. In partnering with the DOE Atmospheric System Research (ASR) program, ARM solicited a multi-agency Site Science Team approach to provide input and close interaction with ARM management towards a successful SE U.S. deployment of the ARM third Mobile Facility (AMF3) (Miller et al. 2016). These efforts included identifying key locations, science drivers and instruments, and measurement strategies to address the wider climate-process needs and ESM improvement. Community input served a vital role in establishing, refining, and informing the relevant drivers and decisions regarding this AMF3 deployment.

The team has identified Northern Alabama (N. AL) as regionally representative to unlock the key opportunities that will improve our understanding and model representation of aerosol, cloud, and land-surface processes and their couplings in the SE U.S. A defining aspect of the AMF3 deployment is its commitment to long-term (anticipated five-year) observations to mitigate potential seasonal-to-annual variability that often limits appropriate attribution of phenomena to local or larger-scale processes. The proposed location may leverage nearby surface networks and multi-agency and partner assets to enrich this multi-year deployment. One motivation is to understand the role of spatiotemporal variability (thermodynamic, land-surface) across aspects of the climate system, with our AMF3 team anticipating future demands on characterizing the relationships between local-to-regional cloud development and surface processes across a diverse patchwork of natural, managed, and urban landscapes as found throughout the N. AL regions.

The main site targets an intact, representative, forested region – the Bankhead National Forest (BNF) – underscoring further team commitment to regionally important land-atmosphere two-way interactive studies *"from the canopy to the clouds"*, with enhanced tower instrumentation augmenting traditional ARM capabilities adjacent to this site. Multiple supplemental sites will also be distributed across this region, prioritizing added needs for biodiversity. Anticipated high-priority cloud science themes will target N. AL as a regional SE U.S. hotbed for high-impact weather, convective cloud onset, and shallow-to-deep cloud transitioning. Anticipated aerosol drivers will focus on chemical processes that control the evolution of organic aerosol, the seasonality and spatial distribution of water vapor and particle-phase water, and its role on aerosol optical properties. Anticipated land-atmosphere drivers consider the two-way feedbacks between surface influence on aerosols, clouds, and precipitation properties and the associated radiative impacts on plant physiology and canopy-scale fluxes. Emphasis will include the study of the impact of surface processes on aerosols via precursor emission, and on clouds via moisture flux and thermal development.

Acknowledgments

The Site Science Team acknowledges several individuals that helped inform the site plans, images, and/or other science drivers/motivations in this document. From the U.S. Forest Service, the team is grateful to the efforts of Andy Scott and Shane Hoskins in helping to establish feasible plans for ARM's deployment to the Bankhead National Forest in the vicinity of the Black Warrior Work Center. These efforts would also not have been possible without the engagement of several individuals at the University of Alabama – Huntsville (Kevin Knupp, John Mecikalski, Shanhu Lee, Lawrence Carey, Sean Freeman, Preston Pangle, and John Christie) for extended discussions, campaign presentations, site visits, access to pre-campaign regional data sets, and other support. Similarly, we call attention to the Alabama A&M University and its faculty members Monday Mbila, Wubishet Tadesse, and others for their discussions on the region, visitations to university/urban facilities, and other resources useful in team planning. The team also thanks contributors in the ASR/ARM and wider climate community who directly assisted with materials, management, and related discussions for town halls, workshops, or breakout sessions such as Tim Wagner (University of Wisconsin), Max Grover (ANL), Robert Jackson (ANL), Sebastien Biraud (LBNL), David Romps (LBNL), Rusen Oktem (LBNL), Adam Varble (PNNL), Manishkumar Shrivastava (PNNL), Greg Starr (University of Alabama, Tuscaloosa), Girish Raghunathan (Cleveland State University), Hsi-Yen Ma (LLNL), Marc Calaf (University of Utah), Marcus van Lier-Walqui (Columbia University), Toshihisa Matsui (University of Maryland), Matthew West (University of Illinois, Urbana-Champaign), William Gustafson Jr. (PNNL), and Yunyan Zhang (LLNL). Finally, the team acknowledges their corresponding ARM infrastructure partners, mentors, translators, and web communications and operations personnel for all their efforts towards the development of the plan/design/materials for this site, and its socialization within the DOE, ARM, and extended climate community. We give special thanks to the operations team at Sandia National Laboratory (Joe Hardesty, Lori Parrott, Fred Helsel, and Mark Ivey) for supporting initial site evaluations, ARM staff at Argonne National Laboratory (Patty Campbell, Nicki Hickmon, Mike Ritsche, Mark Spychala, and Adam Theisen) for supporting site development and operations, and Jim Mather (PNNL), Jennifer Comstock (PNNL), and Giri Prakash (ORNL), among many others, for management/instrumentation support.

Acronyms and Abbreviations

1D	one-dimensional
3D	three-dimensional
4D	four-dimensional
AACT	ARM-ASR Coordination Team
AAF	ARM Aerial Facility
ABL	atmospheric boundary layer
ACES	Alabama Cooperative Extension System
ACPC	Aerosol, Cloud, Precipitation, and Climate Working Group
ACSM	aerosol chemical speciation monitor
ADC	ARM Data Center
AERI	atmospheric emitted radiance interferometer
AERIoe	AERI optimal estimation
AETH	aethalometer
AGL	above ground level
AGU	American Geophysical Union
AI	artificial intelligence
AMF	ARM Mobile Facility
AMF3	Third ARM Mobile Facility
AMSG	Aerosol Measurement Steering Group
ANL	Argonne National Laboratory
AOD	aerosol optical depth
AOP	Airborne Observing Platform
AOS	Aerosol Observing System (ARM), Atmosphere Observing System (NASA)
APS	aerodynamic particle sizer
ARCSIX	Arctic Radiation-Cloud-Aerosol-Surface-Interaction Experiment
ARM	Atmospheric Radiation Measurement
ARR	Ameriflux Rapid Response
ARSCL	Active Remote Sensing of Clouds
ASCENT	Atmospheric Science and Chemistry Measurement Network
ASCII	American Standard Code for Information Interchange
ASR	Atmospheric System Research
AVIRIS	Airborne Visible/Infrared Imaging
AVIRIS-NG	Airborne Visible InfraRed Imaging Spectrometer-Next Generation
BAECC	Biogenic Aerosols-Effects on Clouds and Climate
BB	biomass burning

BER	Office of Biological and Environmental Research
BERAC	Biological and Environmental Research Advisory Committee
BL	boundary layer
BNF	Bankhead National Forest
BNL	Brookhaven National Laboratory
BRDF	bi-directional reflectance distribution function
BWWC	Black Warrior Work Center
CACTI	Cloud, Aerosol, and Complex Terrain Interactions
CAPS	cloud aerosol and precipitation spectrometer
CBL	convective boundary layer
CCN	cloud condensation nuclei, cloud condensation nuclei particle counter
CEIL	ceilometer
CIMS	chemical ionization mass spectrometer
CIN	convective inhibition
CO2FLX	carbon dioxide flux measurement system
COA	Certificate of Authorization
COGS	Clouds Optically Gridded by Stereo
CPC	condensation particle counter
CPCF	condensation particle counter – fine
CPCU	condensation particle counter – ultrafine
CPMSG	Cloud and Precipitation Measurement Steering Group
CSAPR2	C-band Scanning ARM Precipitation Radar (second generation)
CSN	Chemical Speciation Network
DL	Doppler lidar
DOE	U.S. Department of Energy
DOI	Digital Object Identifier
DQPR	Data Quality Problem Reporting
DTS	distributed temperature sensor
E3SM	Energy Exascale Earth System Model
EC	eddy covariance
ECOR	eddy correlation flux measurement system
EMIT	Earth Surface Mineral Dust Source Investigation
EMSL	Environmental Molecular Sciences Laboratory
EPA	Environmental Protection Agency
ESM	Earth system model
ESS	Earth System Science, Environmental System Science (DOE)
ET	evapotranspiration
FIA	Forest Inventory and Analysis

fPAR	fraction of photosynthetically active radiation
GEWEX	Global Energy and Water Exchanges
GHG	greenhouse gas
GIF	Guest Instrument Facility
GLAFO	GEWEX Land-Atmosphere Feedback Observatory
GLASS	Global Land-Atmosphere System Studies
GOES	Geostationary Operational Environmental Satellite
GPM-GV	Global Precipitation Measurement-Ground Validation
HPC	high-performance computing
HR-AMS	high-resolution aerosol mass spectrometer
HTDMA	hygroscopicity tandem differential mobility analyzer
ICLASS	Integrated Cloud, Land-surface, and Aerosol System Study
IMPROVE	Interagency Monitoring of Protected Visual Environments
INP	ice nucleating particle
INTERPSONDE	Interpolated Sonde VAP
IOP	intensive operational period
IRT	infrared thermometer
KaSACR	Ka-band Scanning ARM Cloud Radar
KAZR	Ka-band ARM Zenith Radar
LAI	land-atmosphere interactions
LANL	Los Alamos National Laboratory
LaRC	Langley Research Center
LASSO	Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation
LBNL	Lawrence Berkeley National Laboratory
LD	laser disdrometer
LDQUANTS	Laser Disdrometer Quantities VAP
LES	large-eddy simulation
LLNL	Lawrence Livermore National Laboratory
LMA	Lightning Mapping Array
LoCo	land-atmosphere coupling
LSM	land surface model
LWP	liquid water path
M1	Main Facility
MC3E	Mid-latitude Continental Convective Clouds Experiment
MCS	mesoscale convective system
MET	surface meteorology system
MDP	Mobile Deployment Platform
MFRSR	multifilter rotating shadowband radiometer

ML	machine learning
MOST	Monin-Obukhov Similarity Theory
MPL	micropulse lidar
MWR	microwave radiometer
MWRRET	Microwave Radiometer Retrievals VAP
NALMA	Northern Alabama Lightning Mapping Array
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NEE	net ecosystem exchange
NEON	National Ecological Observatory Network
NEON TALL	NEON Talladega
NEPH	nephelometer
NetCDF	Network Common Data Form
NEXRAD	Next-Generation Weather Radar
NOAA	National Oceanic and Atmospheric Administration
NPF	new particle formation
NSF	National Science Foundation
NWS	National Weather Service
OA	organic aerosol
OACOMP	Organic Aerosol Component VAP
OC	organic carbon
OLI	Oliktok Point, Alaska
OPC	optical particle counter
ORNL	Oak Ridge National Laboratory
P	pressure
PAR	photosynthetically active radiation
PASCCALS	Process-Level Advancements of Climate through Cloud and Aerosol Life Cycle Studies
PBAP	primary biological aerosol particle
PERiLs	Propagation, Evolution, and Rotation in Linear Storms
PGSISO	precision gas system isotope analyzer
PI	principal investigator
PNNL	Pacific Northwest National Laboratory
POPEYE	Profiling at Oliktok Point to Enhance YOPP Experiments
POPS	portable optical particle spectrometer
PSAP	particle soot absorption photometer
PTR-MS	proton transfer reaction-mass spectrometer
QA	quality assurance

QC	quality control
QLCS	quasi-linear convective system
rBC	refractory black carbon
RGB	red-green-blue
RH	relative humidity
RHI	range height indicator
RL	Raman lidar
RWP	radar wind profiler
SACR	Scanning ARM Cloud Radar
SAIL	Surface Atmosphere Integrated Field Laboratory
SBG	Surface Biology and Geology
SEAC4RS	Studies of Emissions, Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys
SEBS	surface energy balance system
SELARO	Southeast Land-Atmosphere Research Opportunities
SFA	Science Focus Area
SGP	Southern Great Plains
SIF	solar-induced fluorescence
SIRS	solar infrared radiation station
SKYRAD	sky radiometer
SMPS	scanning mobility particle sizer
SOA	secondary organic aerosol
SOAS	Southern Oxidant & Aerosol Study
SONDE	radiosonde
SP2	single-particle soot photometer
SST	Site Science Team
STAC	Science and Technology Advisory Committee (EMSL)
STAMP	soil temperature and moisture profiles
sUAS	small uncrewed aerial system
T	temperature
TBRG	tipping-bucket rain gauge
TBS	tethered balloon system
TCCON	Total Carbon Column Observing Network
TEMPO	Tropospheric Emissions: Monitoring Pollution
TLS	terrestrial lidar scanner
TOWERMET	facility-specific multi-level meteorological instrumentation
TRACER	Tracking Aerosol Convection Interactions Experiment
TSI	total sky imager

UAH	University of Alabama, Huntsville
UEC	User Executive Committee
UAS	uncrewed aerial system
UAT	University of Alabama, Tuscaloosa
UHSAS	ultra-high-sensitivity aerosol spectrometer
UPS	uninterruptible power supply
USDA	United States Department of Agriculture
USFS	United States Forest Service
VAP	value-added product
VARANAL	Constrained Variational Analysis VAP
VCP	volume coverage patterns
VDIS	video disdrometer
VDISQUANTS	Video Disdrometer VAP
VISST	Visible Infrared Solar-Infrared Split Window Technique
VOC	volatile organic carbon
VORTEX-SE	VORTEX Southeast
VPD	vapor pressure deficit
WIBS	wideband integrated bioaerosol sensor
WRF-Chem	Weather Research and Forecasting (WRF) model coupled with Chemistry
XSACR	X-band Scanning ARM Cloud Radar
YOPP	Year of Polar Prediction

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1.0 Background and Introduction

An Atmospheric Radiation Measurement (ARM) Mobile Facility (AMF) deployment to the southeast United States (SE U.S.) provides unique opportunities to study important land-atmosphere interactions and processes. Extended ARM observations distributed across the diverse northern Alabama (N. AL) landscape will help resolve the role of local forcing in climate-relevant processes and differentiate those from climate processes driven by larger-scale circulations. We anticipate these efforts will advance community understanding of how regional processes or feedbacks influence the longer-term patterns of climate variability. A distinguishing factor for Third ARM Mobile Facility (AMF3) studies will be its deployment within the Bankhead National Forest (BNF), promoting regionally important SE U.S. land-atmosphere two-way interactive studies *"from the canopy to the clouds*." This long-term commitment to land-atmosphere-cloud interaction studies will be bolstered by unique tower-based observations coupled with traditional ARM atmospheric profiling excellence and distributed ARM and partner resources throughout the wider region.

The SE U.S. is home to significant terrain and land-surface complexity, and many of its characteristic features are also represented in the selected N. AL domain. Key science drivers for this region include: (i) the role of energy and mass fluxes in boundary-layer dynamics, convection, and aerosols, (ii) the two-way interactions between plant physiological functioning and aerosol and cloud properties, and (iii) processes mediated through changes in radiation and the biogenic emission of aerosol precursors. While the fluxes (e.g., transpiration) and states (e.g., albedo, height) of vegetation can influence atmospheric processes (Vilà-Guerau de Arellano et al. 2023), daily-to-seasonal dynamics in atmospheric moisture (e.g., vapor pressure deficit, VPD) and other conditions (e.g., soil moisture) mediate vegetation physiological function (F. Li et al. 2023, W. Li et al. 2021, Novick et al. 2016), representing another critical feedback between the atmosphere and land surface. The atmospheric conditions, with boundary-layer humidity as a prime example, depend strongly on the entrainment of dry air into the top of the boundary layer, and on the behavior of the residual layer during the night. In turn, boundary-layer humidity has a strong impact on a variety of coupled processes, including plant carbon, water, and energy cycling, as well as the Bowen ratio, and convection itself (Vilà-Guerau de Arellano et al. 2014). Short-term plant physiology is also strongly tied to ambient environmental conditions including downwelling shortwave radiation, temperature, and VPD (Bernacchi et al. 2013). Changes in atmospheric optical properties, either through cloud cover or aerosol loading (e.g., aerosol optical depth), may enhance plant carbon uptake by increasing the diffuse fraction of radiation (Gu et al. 2002). Ground-based sites have observed this "diffuse fertilization" effect (e.g., Gu et al. 1999, Oliphant et al. 2011, Rap et al. 2018, Urban et al. 2012), although the long-term effects on global carbon sequestration is unclear and may be relatively small (Keppel-Aleks and Washenfelder 2016, Zhu et al. 2019).

Ambient environmental conditions and plant stress can also influence biogenic volatile organic carbon (VOC) emissions (Feldner et al. 2022, Pikkarainen et al. 2022, Rissanen et al. 2022), and the fluxes of VOCs and resulting secondary organic aerosols (SOAs) represent a potential feedback loop between the biosphere and atmosphere (Steiner, 2020). Modeling studies have shown this feedback (Rap et al. 2018), but ground-based observations suggest only a weak or non-existent carbon signal (Keppel-Aleks and Washenfelder 2016). A better understanding of (i) the environmental drivers of surface-atmosphere coupling, (ii) reconciling the model-data mismatch under diffuse light influences on plant function and atmospheric feedbacks, and (iii) the role of cloud cover in the SE U.S. are essential for improved model predictions of climate change impacts in the region.

From the perspective of long-standing ARM and ASR motivations in cloud processes and life cycle studies, the N. AL region is an attractive accelerant to existing ARM Southern Great Plains (SGP) facility efforts in Oklahoma and marries well within ARM midlatitude cloud campaigns and tropical-to-maritime continent convective cloud deployments. The regional cloud conditions include ubiquitous shallow-to-deep convection, with strong seasonal variability in environmental and aerosol forcings that promote isolated and organized convection to different levels of intensity. Heightened low-to-mid tropospheric humidity contrasts with fixed-site SGP conditions, (Figure 1), promoting frequent clouds that act as a natural laboratory for process studies and sensitivity testing for convective clouds and associated controls. The propensity for this N. AL domain to experience severe convection including mesoscale convective systems (MCS), quasi-linear convective systems (QLCS), and isolated supercell thunderstorms is also of high importance for monitoring and evaluating the potential increases in convective intensity, cloud coverage area, or precipitation rates under future climate change scenarios.

These trends include the wider SE U.S. as potentially experiencing more frequent and more severe precipitation, with impacts already being suggested from extended radar observations (Feng et al. 2018, Prein et al. 2020). Moreover, the higher humidity across this region coincides with a strong gradient in the nature of the precipitation that reaches the surface (stratiform precipitation fraction, i.e., the ratio of non-convective core precipitation to total precipitation, increasing towards the east), potentially associated with less evaporation of anvil rainfall in the more humid SE U.S. lower atmosphere (Figure 1). A shift from more widespread/trailing stratiform-type precipitation (as at SGP) to scenes dominated by less aggregated convection in N. AL highlights the contrast anticipated between the sites, including shifts in the frequency of baroclinic waves associated with MCS and/or propensity for surface-driven convective clouds. More immediately, the common and isolated nature of convective clouds over N. AL will offer new opportunities for frequent cloud sampling and studies of local convective processes and environmental controls. However, any shift in precipitation type between the SGP and the BNF site, including current and future climate, also suggests variability in the vertical structure of diabatic heating and subsequent feedback to the global circulation, as well as land surface (e.g., plant growth, soil moisture) characteristics.

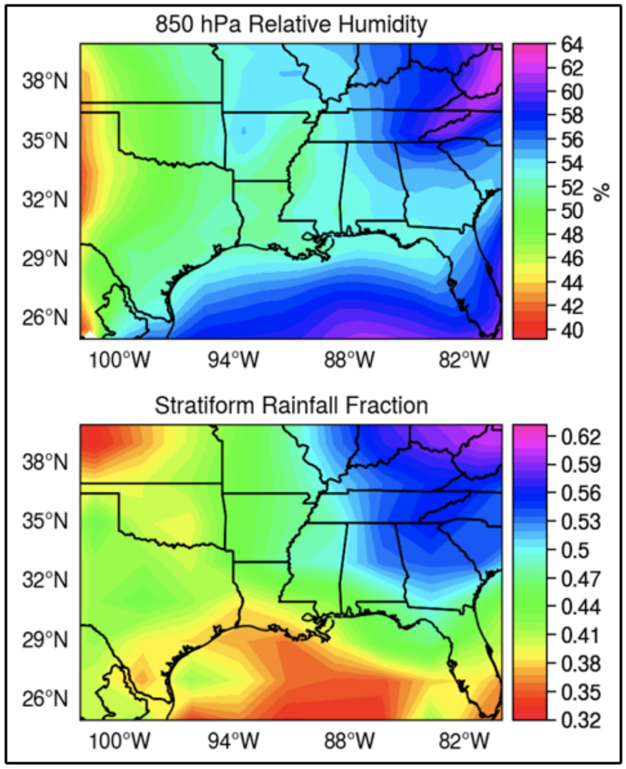

Figure 1. 850 hPa relative humidity and stratiform rainfall fraction climatologies derived from satellite platforms.

Importantly, the AMF3-BNF deployment was collaboratively sited with the guidance of the ARM user facility and the ASR program, incorporating these efforts towards wider climate-community input and investment in the resulting sites. To accomplish these objectives, a Site Science Team was selected to advise on the key regional scientific opportunities, advocate for current ARM resources and emerging technologies of interest for this campaign, and closely interact with ARM management towards a successful site selection, deployment, and tenure of this AMF3. The assembled team recommended this N. AL region from among several candidate regions according to community-preferred siting criteria, workshops, and other input that included balancing scientific and practical considerations such as proximity to complex terrain, proximity to coastal regions, representative forested land cover and land-use diversity, representative air mass or regional aerosol sources, cloud frequency and severity, allowable air-space for aerial observations, and proximity to partner facilities. A core tenet for recommending the N. AL region for this campaign was the diversity of landscapes (forested, agricultural, and urban), including the expansive Bankhead National Forest and the Huntsville, Alabama population center with numerous partner facilities and resources. The region offers a significant contrast in complexity to existing ARM SGP observational records in terms of horizontal heterogeneity across several key scientific drivers, while being tenable to ARM asset placement (i.e., scanning radars). Overall, the team was influenced by N. AL as a regional maximum for high-impact weather, as well as its proximity to high-quality air monitoring, aerosol sampling, and land-atmosphere networks.

2.0 Overview of Science Objectives and Key Questions

The AMF3-BNF deployment is a unique opportunity to improve coupled aerosol, cloud, and land surface understanding (Figure 2) and ESM process-level representation in an environment where such processes are strongly driven by local forcing. A defining aspect of the AMF3-BNF deployment is an expectation for long-term (~five-year) observations to mitigate potential seasonal-to-annual variability that limits appropriate capture or attribution of local-to-larger-scale processes or phenomena. Understanding the role of spatiotemporal variability (e.g., thermodynamic, land-surface) across aspects of the climate system is a key motivator for AMF3-BNF studies, especially for characterizing the relationships between local-to-regional cloud development and surface processes across a diverse patchwork of natural, managed, and urban landscapes found across the N. AL domain.

An overarching theme for the AMF3 efforts is scale aggregation in ESMs, coupling aerosol-cloud-land surface processes (Figure 2), from cloud to regional scales. Such finer-scale efforts are timely as of this writing, as the DOE Energy Exascale Earth System Model (E3SM) targets a global 3-km grid resolution on a decadal timescale. Observing and representing these coupled processes necessitates the detailed and creative capabilities as available from multi-disciplinary DOE ARM instrumentation that similarly scales from column/profiling to regional land-surface, atmospheric aerosol, and cloud properties.

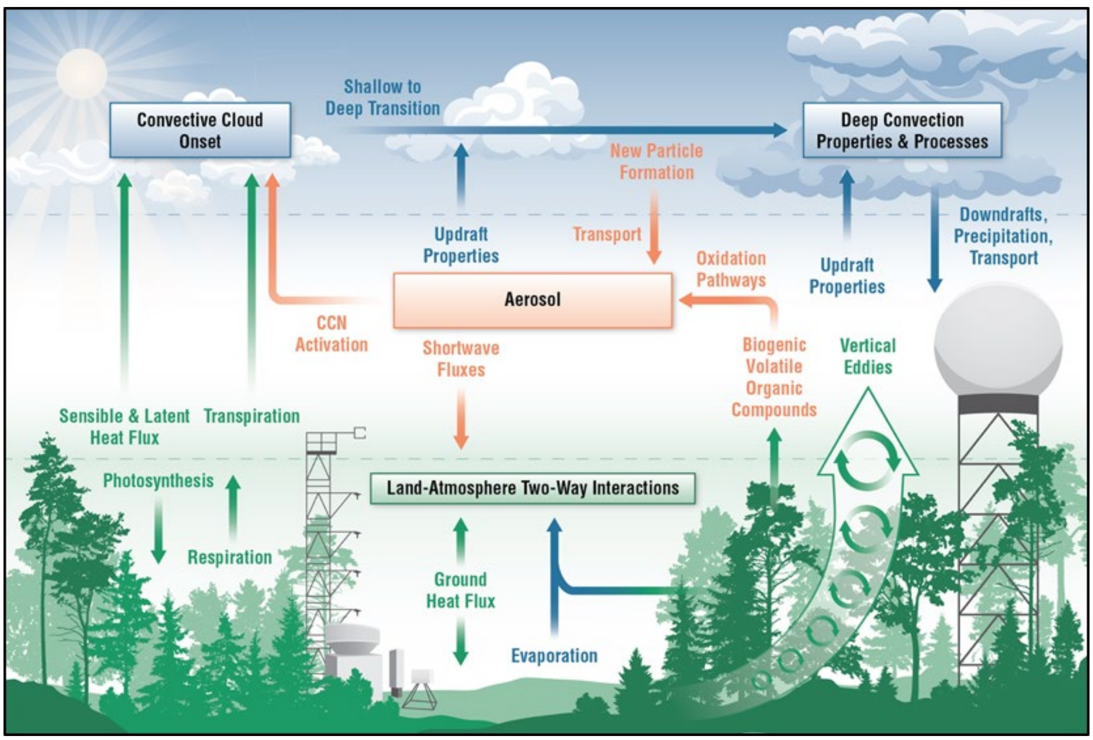

Figure 2. Conceptual schematic illustrating SE U.S. topical areas, associated science drivers, and cross-cutting science themes.

This section identifies several coupled aerosol-cloud-land surface activities relevant to the wider SE U.S., or opportunities we believe are achievable over a multi-year ARM deployment to the N. AL region (Figure 3). The anticipated efforts include multiple cross-cutting areas of interest for ESMs and their continued advancement (Figure 2). Although the key science priorities and questions in this section have been compiled with feedback from the climate community, an exhaustive list of potential topics is not provided nor should be limited by this Science Plan. We envision that this multi-year ARM deployment, and its associated scientific priorities, will evolve to incorporate additional topics, including those possible only when newer capabilities emerge. We also anticipate such opportunities to arise with regional or other agency partners and principal investigators (PIs). This flexibility to solicit and embrace new opportunities of community interest, as from emerging technologies or intensive operational periods (IOPs), was a hallmark of the previous ARM AMF3-Oliktok Point team activities. In following their lead, our team will support continued science workshops/breakout sessions through DOE, other open-community feedback, and mechanisms to refine or incorporate science drivers and priorities that emerge throughout this deployment.

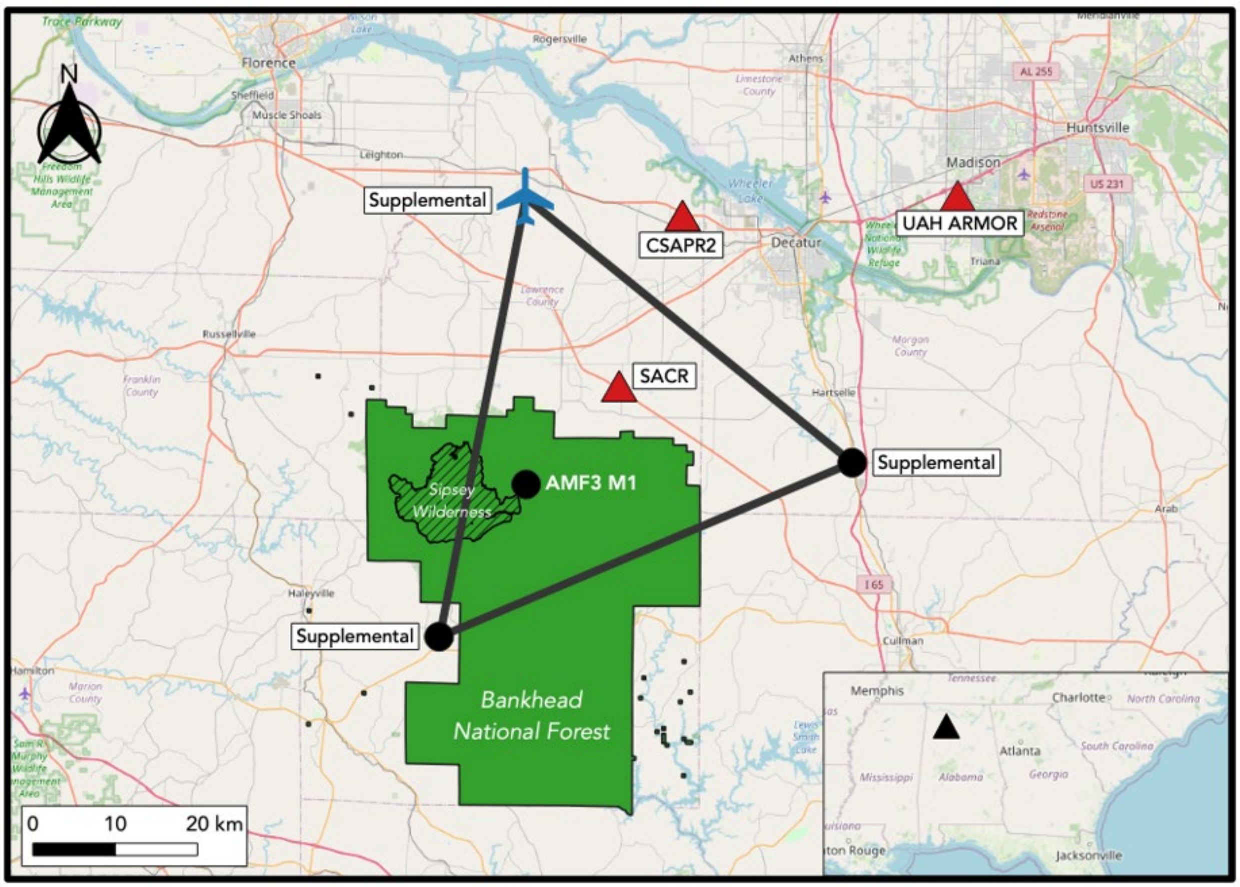

Figure 3. Proposed design schematic for possible AMF3 site layouts in the N. AL region and nearby partner locations.

2.1 Aerosol Research

Atmospheric aerosols range in size by several orders of magnitude (from nanoparticles ~ 1 nanometer to coarse-mode particles 10-100 microns in diameter), vary greatly in source and composition, and can undergo a range of chemical processes in the atmosphere that influence their atmospheric lifetime from hours to weeks. Aerosols can derive from primary sources (e.g., primary emissions of coarse-mode aerosols such as dust and pollen), secondary formation in the atmosphere (e.g., gas-to-particle partitioning and heterogeneous chemistry), and new particle formation (NPF) from the photochemical reaction of gas-phase precursors, with wet/dry deposition as dominant sinks. Important aerosol properties include their number concentration, size, chemical composition, water-uptake (sub- and super-saturated), and optical properties (e.g., absorption, scattering). Aerosols are an important contributor to climate forcing on local to global scales due to their direct interactions with incoming solar radiation through scattering and absorption, and indirectly via their role as cloud condensation nuclei (CCN; Albrecht 1989, Charlson et al. 1992, Twomey 1974) and ice nucleation particles (Fröhlich-Nowoisky et al. 2016). Over the SE U.S. in particular, accurate assessment of the relationship between CCN and forcing in global climate models requires an understanding of the aerosol processes and properties that control the CCN budget (Carlton et al. 2018).

Key aerosol science questions for the AMF3-BNF include:

- *What are the mechanisms responsible for new particle formation and growth as well as its impacts on boundary-layer CCN number budget?*
- *What chemical processes control the formation of secondary organic aerosol and their potential as CCN?*
- *To what extent do primary biological aerosol particles contribute to CCN and ice nucleating particle (INP) populations?*
- *What is the seasonality and spatial distribution of aerosol hygroscopic properties, and their connection to aerosol chemical composition?*
- *What is the role of particle-phase water on aerosol optical properties?*
- *What chemical and physical processes control aerosol optical properties?*
- *What is the role of biomass burning (BB) on regional radiative forcing?*

2.1.1 Atmospheric Aerosol Processes

An important factor affecting the particle size dynamics in the atmosphere, and thereby their impacts on climate, is the balance between particle production rate (determined by NPF and subsequent growth, primary particle emissions), and the rate at which particles are lost due to dry and wet deposition (Carlton et al. 2018). While NPF is known to be an important aerosol source in many regions (Kerminen et al. 2005, Laaksonen 2005), the contribution of NPF to boundary-layer aerosol in the SE U.S. is poorly understood due to limited measurements over short time periods (Carlton et al. 2018, Lee et al. 2016). Observations from other forested sites (e.g., ARM's Biogenic Aerosols-Effects on Clouds and Climate [BAECC] and Surface Atmosphere Integrated Field Laboratory [SAIL] campaigns) suggest that NPF may be highest in spring and fall. NPF above the atmospheric boundary layer followed by downward transport to the surface may also be a significant source of new aerosol (H Chen et al. 2018, Wang et al. 2016, Zheng et al. 2021), demonstrating the importance of vertically resolved measurements of atmospheric composition. Primary biological aerosol particles (PBAP) have been observed in forests (Huffman et al. 2013). This has wide-ranging atmospheric implications, including acting as ice nucleating particles to trigger ice formation in mixed-phase clouds (Fröhlich-Nowoisky et al. 2016). The effects of bioaerosols on ice nucleation in clouds depends both on their ice active properties and their vertical distribution in the atmosphere. The propagation of PBAP from the surface to the troposphere and their long-range transport are both active areas of research in which PBAP have been detected throughout the troposphere (Zawadowicz et al. 2019) and in the stratosphere (Bryan et al. 2019) and have been shown to be transported across the continents (Mayol et al., 2017). The recent increase in the frequency and severity of wildfires has left substantial knowledge gaps in several key areas surrounding emissions of primary BB particles and trace gases. The primary removal mechanisms of trace gases and aerosols are dry deposition (e.g., uptake to soil, vegetation, and pre-existing aerosol) and wet deposition (e.g., absorption into droplets followed by precipitation or droplet impaction). These processes are poorly understood and may be characterized by large spatial and temporal heterogeneity (Farmer et al. 2021).

Biogenic volatile organic compounds (VOC) such as isoprene and monoterpenes that are plentiful in the SE U.S. play an important role in the evolution of secondary organic aerosol (SOA) particles. The role of oxides of nitrogen (NO_x) in this process is crucial for understanding how current anthropogenic emissions as well as past pre-industrial' pristine conditions regulate global aerosol populations. While it has been estimated that more than half of monoterpene-derived SOA in the U.S. currently originates from NO_3 radical oxidation (Pye et al. 2010), SOA yields and NPF from terpene oxidation show significant variability for different precursors (Fry et al., 2014). SOA yields for OH- or O_3-initiated oxidation under both low and high NO_x conditions also show large variability with precursor compounds (Ng et al. 2017, L. Xu et al. 2018). Recent field observations show that NO_x can play a complex role in SOA formation: increases in processed NO_x can lead to increased monoterpene SOA while monoterpene fragmentation (and therefore species volatility) also increases (H. Zhang et al. 2018). One interpretation is that low NO_x leads to less abundant, lower-volatility compounds that can participate in NPF, whereas in high NO_x environments, a larger pool of condensable compounds is generated.

2.1.2 Aerosol Direct Impacts on Radiation

Studies have been unable to reconcile high aerosol optical depth (AOD) satellite observations with ground-based observations of ground-level aerosol mass concentrations (PM2.5) (Christiansen et al. 2019, Ford and Heald 2013). Numerous hypotheses have been put forth to explain this discrepancy, including the presence of an unknown biogenic source of organic aerosol (Goldstein et al. 2009) and a missing source of aerosol above the surface layer (Ford and Heald 2013). A recent study concluded that current ground-based observations in the SE U.S. are insufficient for radiative closure studies of AOD (Christiansen et al. 2019), stating that "the development and application of methods that chemically identify individual compounds in different organic carbon (OC) volatility fractions is a critical open area and may improve understanding of PM2.5-AOD relationships over long time periods and large spatial scales to better reconcile satellite- and surface-based measurements." The co-deployment of remote-sensing instruments, combined with modeling, can inform the relationship between ground-based observations of aerosol properties and satellite measurements of AOD. The proposed AMF3-BNF deployment provides a unique opportunity to address the gaps of prior observations, particularly about long-term observations of aerosol particle chemical, microphysical, and optical properties.

One type of aerosol with strong direct forcing potential is that from BB aerosol. Analysis of measurements from AMF3-BNF will improve the characterization of BB optical properties, and provide well-characterized, long-term surface measurements that can motivate future studies of the vertical profile of BB aerosols and their net effect on radiative forcing. Prescribed fires are frequently employed to eliminate excess agricultural byproducts after crop harvesting (Dennis et al. 2002). During the 2013 Studies of Emissions, Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys (SEAC4RS) campaign, agricultural fire emissions were measured in the Mississippi River Valley, resulting in high levels of primary organic aerosol (OA) emissions (X. Liu et al. 2016). Agricultural burning exhibits strong seasonal tendencies, with a small emissions peak in June, and greater emissions from September to November (Korontzi et al. 2008). The vertical profile of BB aerosol concentrations is known to be an important indicator for the sign of the net radiative forcing, with the scattering and absorbing characteristics depending on cloud conditions and relative position of the BB aerosol, triggering changes in the sign of radiative forcing (Jacobson 2005, Penner et al. 2003, Keil and Haywood 2003). In addition, BB aerosols in clouds can bring about evaporation of cloud droplets, decrease in cloud coverage, and disruption of atmospheric circulation dynamics through the semi-direct effect. The AMF3 AOS (Uin et al. 2019) deployment will provide key measurements of surface-observed (and potentially aerial-observed) BB aerosol microphysical, chemical, and optical properties that are unique to ARM capabilities and central to why ARM deployments to these regions are critical.

2.1.3 Aerosol Indirect Impacts on Radiation

Organic compounds comprise a major fraction of fine particle mass in the SE U.S. (Q. Zhang et al. 2007) and have the potential to influence cloud processes through the formation of CCN (Levin et al. 2014). Prior studies indicate that long-term surface observations can be useful for understanding seasonality in hygroscopicity in the SE U.S. (L. Xu et al. 2015), a region impacted by seasonality in the emission of biogenic VOCs and in agricultural burning. The AMF3-BNF enables the use of long-term measurements to address the chemical composition and the hygroscopicity of aerosols at the surface, with a specific focus on the organic fraction – as this is a large component of the regional aerosol composition and remains the most unconstrained. The extent to which this observed seasonality in organic aerosol composition contributes to seasonality in observed surface hygroscopicity is an open question. Additionally, primary biological aerosols such as dust and pollen have the potential to act as INP, also influencing cloud formation.

While surface-level measurements provide important information on aerosol properties and their potential as CCN and INP, an understanding of the coupling between the surface layer and the upper regions of the boundary layer is needed to fully assess their actual impacts on cloud properties. Therefore, measurements of boundary-layer structure, including turbulence, heterogeneity, and depth, are critical observations for this research, and will be assessed together with surface-layer aerosol properties. To improve regional process-level NPF understanding, the site will help investigate the role of vertical transport of NPF-aloft as a source of boundary-layer aerosol, and the role of condensational growth of aerosol to CCN-active sizes. The AMF3 deployment will also provide long-term surface measurements of the aerosol size distribution to establish a baseline for evaluating the seasonality, frequency, and resulting aerosol formation and growth rates needed to characterize surface-observed NPF in the region (Kerminen et al. 2018).

2.2 Convective Cloud Research

Northern Alabama is affected by strongly forced synoptic-scale weather systems during the spring/fall seasons leading to outbreaks of organized severe thunderstorms that include supercells and mesoscale convective systems. The mesoscale conditions in these severe weather events differ from their counterparts in the U.S. Central Plains because of larger free tropospheric moisture, a prevalence of mixed convective cloud modes, and the more frequent occurrence of severe weather at night. During the summertime, this region is favorable for the study of weakly sheared convective clouds that are strongly influenced by local variability (e.g., variability not resolved at scales < O[10s of km]) rather than larger-scale features (e.g., fronts, convergence boundaries, and low-level jets). As in the shoulder seasons, these less organized summer convective environments often exhibit larger moisture in the boundary layer and in the free troposphere when compared to SGP. The depth of the daytime convective boundary layer is also shallower than found at SGP due to differences in the spatiotemporal patterns of the Bowen ratio. Finally, aerosol concentrations differ between the SE U.S. and SGP. All these environmental differences contribute to statistically different cloud distributions and behaviors, which in turn leads to a significant impact on the surface energy budget in ways not characteristic of SGP.

Key convective cloud science questions for the AMF3-BNF include:

- *What is the role of local thermodynamic perturbations in the onset of shallow convection?*
- *What are the key atmospheric processes that regulate the transition from shallow-to-deep convection?*
- *What is the role of the surface and prior convection on subsequent mesoscale perturbations?*
- *What environmental characteristics influence the width, depth, and vertical velocities within deep convective updrafts and downdrafts?*
- *How does that nature of convective updrafts relate to the intensity distributions and spatial scales of stratiform precipitation?*
- *How do convective updrafts and downdrafts impact boundary-layer aerosols and canopy profiles?*
- *How do N. AL summertime deeper convection modes and processes compare/contrast to shoulder season convective clouds?*

2.2.1 Understanding the Onset of Convective Clouds and Shallow-to-Deep Transitions

A key motivation for AMF3-BNF research is cloud onset studies, including establishing to what extent mesoscale thermodynamic perturbations that contribute to cloud onset are resolvable by our current observational networks. Horizontal gradients in land-surface type, topography, and previous precipitation are among the expected dominant drivers of mesoscale perturbations. We hypothesize that local (mesoscale) temperature and moisture perturbations conspire to create regions of locally reduced convective inhibition (CIN) and reduced negative entrainment effects as well as local mesoscale circulations, all of which favor initial shallow convective cloud development and potentially the first appearance of precipitating shallow convection. These mesoscale features may also contribute to a widening of moist updrafts with time, eventually leading to deep convection.

The shallow-to-deep transition of moist convection is poorly handled by global climate models due to deficiencies in cumulus parameterizations (Christopoulos and Schneider 2021, Rio et al. 2019). These deficiencies stem from an insufficient understanding of the shallow-to-deep transition at a process level. Possible contributing factors to this transition are the progressive widening of clouds (whose causes are not well established), and a concurrent reduction in the deleterious effects of entrainment. This may be accompanied by mesoscale ascent driven by flow patterns occurring on scales larger than the convective updrafts themselves that act to reduce CIN and moisten the free troposphere, further reducing the negative effects of entrainment. The proposed AMF3-BNF campaign is well-positioned to observationally validate these ideas, via concurrent high spatiotemporal observations of the environment in the vicinity of convection transitioning from shallow to deeper modes, along with key observational tools (i.e., radars, stereo cameras) to investigate the characteristics of the developing convection facilitating joint analyses of convection and environmental characteristics on a range of scales. Another potential topic to investigate is whether the detrainment of moisture into the lower troposphere by shallow convection in repeated diurnal cycles may gradually reduce CIN, reduce entrainment-driven dilution, and promote a transition to deep convection on a timescale of days. The observations at the AMF3 site will shed light on these possibilities, potentially leading to downstream improvements in cumulus parameterizations.

2.2.2 Deep Convective Cloud Processes and Properties

Deep convective clouds regulate the global energy and water cycles through extensive cloud coverage (albedo, radiative impacts) and diabatic heating fingerprints. Thus, deep convection and their precipitating anvil counterparts are also a significant emphasis for this deployment. The potential impacts of climate change on major southeast U.S. population centers may include shifts in thunderstorm intensity, frequency, and longevity (Prein et al. 2020, Seeley and Romps 2015, Trapp et al. 2009). These shifts are important to the N. AL region and the Huntsville urban center particularly, where the population continues to expand and remains increasingly vulnerable to severe convection (Ashley and Strader 2016).

An ongoing challenge in simulating these deeper convective systems is that the factors that regulate cumulus size, draft strength, anvil coverage and precipitation intensity are poorly understood, and may reflect complex surface and boundary layer interactions. Slow advancement is partly attributed to a lack of routine dynamics and microphysical property observations within deeper convective clouds over the variety of attendant larger-scale forcing scenes, including that resulting from heterogeneity of horizontal and vertical distributions of aerosols, moisture, and land use. The AMF3-BNF and surrounding region offers a significant advantage for cumulus cloud studies to complement existing ARM SGP observations – the higher mid-tropospheric humidity promotes more frequent clouds, and when coupled with seasonal variability in convective environments, promotes isolated convection and severe thunderstorms, organized convection in the summertime, and strongly sheared convection during transitional seasons. Accelerating this process-level cumulus updraft understanding requires novel remote-sensing strategies that capitalize on ARM instruments and expertise in convective sampling (Figure 4) (Giangrande et al. 2023, North et al. 2017, Oue et al. 2020).

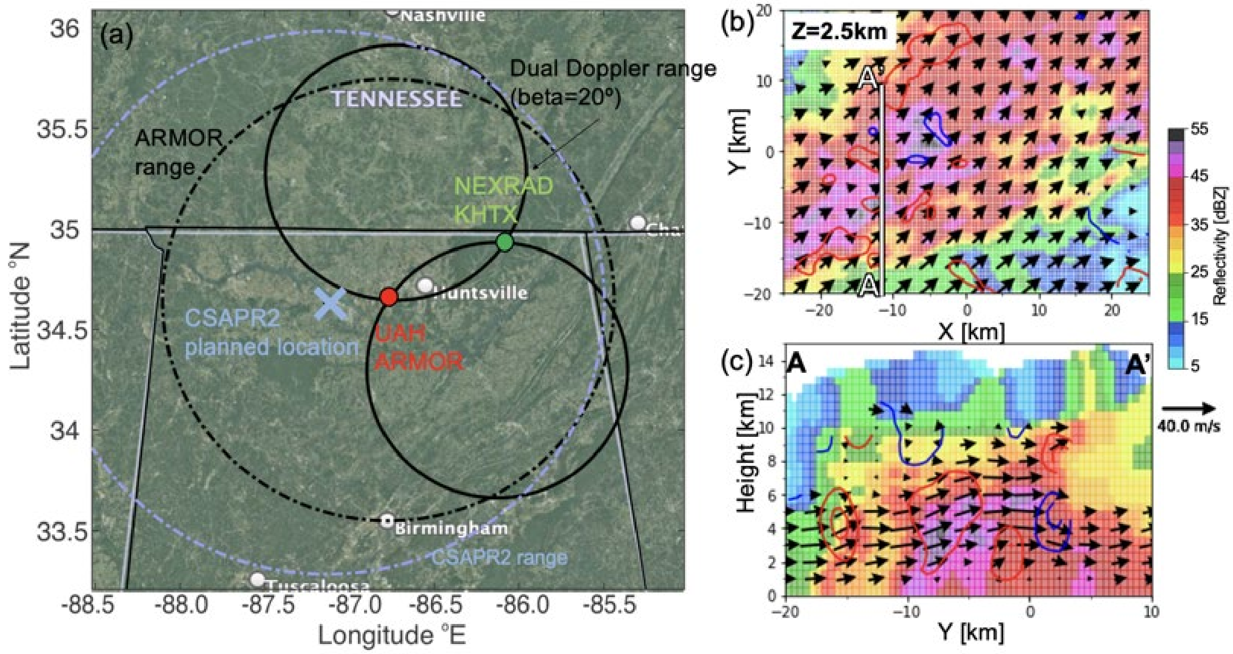

Figure 4. (a) Locations of the current available radars and geometries and C-band Scanning ARM Precipitation Radar (second generation) (CSAPR2) planned location. (b) Horizontal cross-sections of radar reflectivity (color shade) and horizontal wind vector estimated from the Next-Generation Weather Radar (NEXRAD) KHTX and Advanced Radar for Meteorological and Operational Research (ARMOR) for a case of 2023/04/01 07:17 UTC. (c) Vertical cross-sections of radar reflectivity (color shade) and wind vector along A-A' line in (b). Red and black contours in (c) represent updraft and downdraft, respectively, from 5 m s^{-1} with a 5 m s^{-1} increment.

Moreover, convective updraft and downdraft studies in particular are motivated by a need to better understand their role driving the subsequent nature of – and radiative and water cycle implications for – thunderstorm cloud shields. One emphasis is on the relationships between sampled convective drafts and the character of stratiform precipitation processes (Elsaesser et al. 2022, Lin et al. 2021). Shifts in convective cloud behaviors from SGP to AMF3-BNF include a greater proportion of stratiform precipitation near the latter site relative to the former. This implies that regional differences in the dynamical and microphysical processes generate anvils and stratiform precipitation. A larger ratio of stratiform to total precipitation may imply a greater spatial extent of moderate rainfall that more efficiently moistens larger swaths of the land, which can then feedback on mesoscale perturbations and subsequent convective development. Planned instrumentation at the AMF3-BNF site will be well suited to understand what is responsible for these differences. Finally, convective drafts and precipitation are intimately linked to the formation/removal of aerosols in the boundary layer. Recent efforts have suggested that NPF in the outflow regions of deep convection may be an important source of particles to the boundary layer through downward vertical transport (Wang et al. 2016). This transport mechanism may occur through rapid, sporadic downdrafts within deeper convection, in contrast with ideas of comparatively slower and continuous transport into the boundary layer reported for marine regions. These transported particles ultimately grow and maintain the CCN population in the boundary layer, whereas rainfall within these convective drafts may act as a sink for others.

2.3 Land-Atmosphere Interactions Research

The characteristics and dynamics of the land surface – particularly forests, agriculture, and other vegetation types – play a key role in the regulation of surface-atmosphere exchanges of mass and energy, boundary-layer dynamics, and local- to larger-scale atmospheric processes (Barth et al. 2005, Bonan 2008, Helbig et al. 2021, Vilà-Guerau de Arellano et al. 2023). In the SE U.S., a heterogeneous mix of land-cover and land-use types (Figure 5) can drive strong gradients in heat and moisture across the region (Novick and Katul 2020, Stoy et al. 2013), while feedbacks from atmospheric conditions and soil moisture can modulate vegetation functioning (F. Li et al. 2023, Novick et al. 2016, Starr et al. 2016, Yi et al. 2010). For example, land-atmosphere interactions (LAI) set the thermodynamic state of the atmospheric boundary layer (ABL) and influence cloud development through convection via the seasonal exchanges of mass and energy with the boundary layer (Freedman et al. 2001, Sedlar et al. 2022, Vilà-Guerau de Arellano et al. 2014, Williams and Torn 2015). A science goal of AMF3-BNF researchers is to disentangle the influence of local surface interactions, meso-scale circulations, and entrainment from the residual layer and free troposphere.

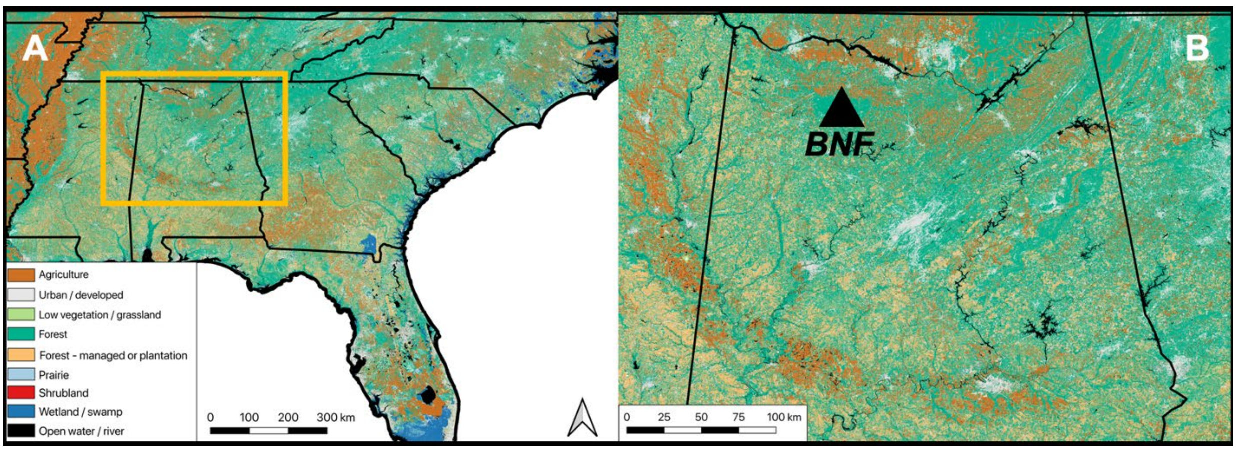

Figure 5. Re-coded and aggregated land-cover and land-use classes derived from the 2016 LandFire (https://landfire.gov/) 30-meter existing vegetation type product for the larger southern U.S. (A) and zoomed into the northern Alabama region (B). The black triangle shows the location of the AMF3 main facility located in the center of the United States Forest Service (USFS) Bankhead National Forest.

Plants also emit aerosols and aerosol precursors into the boundary layer that drive important and complex changes in atmospheric aerosol concentrations (Nagori et al. 2019, L. Xu et al. 2015). The spatio-temporal variability in aerosol source strength is driven by a range of factors including plant physiology, stress, and species (Guenther et al. 2012, Kim 2001, Steiner 2020). These plant ecophysiological controls (e.g., photosynthesis, transpiration) on surface fluxes and precursor emissions are primarily regulated by vegetation responses to meteorological drivers such as radiation, temperature, and moisture (Bonan 2008, Burakowski et al. 2018, Huang et al. 2013, Vilà-Guerau de Arellano et al. 2023). Despite the known importance to boundary-layer processes and the influence on SE U.S. weather and climate, poor process representation of vegetation in models drives large uncertainties in the simulation of surface-atmosphere coupling and feedbacks (Alton et al. 2006, Dietze et al. 2014, Fisher et al. 2018, Rogers et al. 2017, Viskari et al. 2019). These uncertainties limit our ability to forecast the impacts of climate change on the critically important ecosystem services and economy provided by forests and agricultural systems in the SE U.S. (O'Halloran and Bright 2017, G. Sun et al. 2017).

The characteristics of the Northern Alabama region selected for the AMF3-BNF deployment present a novel opportunity for investigating important land-atmosphere two-way interactions. The region reflects a complex mosaic of land cover and land use (Figure 5) that includes urban cities and rural towns, unmanaged and managed forests, including industrial forests, and a range of agriculture uses. Forest cover and structure (Figure 6) varies strongly with land-use history, management activities, and disturbance (Lafon 2010). The region is also a well-known global biodiversity "hot spot" under severe threat by climate change (Costanza et al. 2016). The strong local surface coupling with the atmosphere and the presence of strong emitters of biogenic VOCs implies that vegetation plays a key role in modulating weather patterns. Similarly, air temperature and humidity regulate plant physiology and surface water and energy cycling, and two-way interactions between cloud and aerosol controls on radiation and influence on plant carbon cycling (X Chen and Willis 2022, Meehl et al. 2012, Partridge et al. 2018). Given these challenges, a key objective of this AMF3-BNF deployment is to gain a better understanding of the role of the land surface on boundary-layer dynamics and larger atmospheric processes in the SE U.S., as well as characterize the primary feedbacks and two-way interactions between the atmosphere and the land surface, including the strength and seasonality of these feedbacks. Through detailed surface and vertical profiling measurements and companion remote-sensing and modeling studies, AMF3-BNF measurements will help explore how radiative forcing, heterogeneity in drivers and surface properties, big-leaf versus demographic vegetation scaling (Fisher et al. 2018), and atmospheric and moisture conditions modulate plant functioning – and how this provides a key feedback on atmospheric state and dynamics across the region.

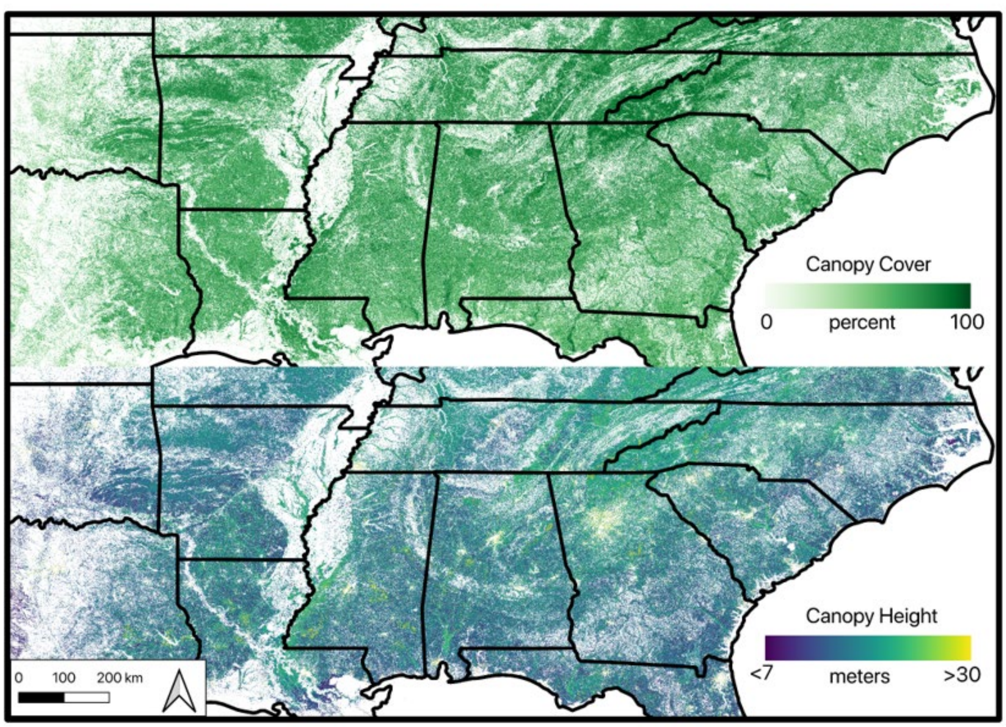

Figure 6. Satellite-derived existing vegetation cover fraction (%) and existing vegetation height (meters) from the 2016 LandFire 30-meter database (https://landfire.gov/).

A core component of the AMF3 will be its use of within-vegetation observation tower(s) (e.g., Section 2.3.1, Section 3.2.2) to allow direct coupling of surface properties with ABL and atmospheric state and dynamics. Leveraging the AMF3 measurement network and this tower infrastructure will provide new opportunities to investigate and model the role of the land surface on weather and climate in the SE U.S. Through anticipated opportunities and partner sites (see also Section 3.5) including the Ameriflux Rapid Response (ARR) program and the National Ecological Observatory Network (NEON), NEON Talladega [TALL]) Mobile Deployment Platform (MDP), as well as individual PI observation networks in the region, the Site Science Team and other PIs could extend the footprint and spatial coverage of the AMF3 network by deploying mobile micrometeorological systems or using existing infrastructure in other surface types (e.g., high-priority surface types such as managed and industrial working forests across a stand-age chronosequence, forest types such as lowland, wet, or deciduous forests). Sub-orbital and orbital remote-sensing platforms provide opportunities to scale up process understanding and provide a larger, regional context to the AMF3 surface and LAI measurement and modeling efforts. These include (as also in Section 3.5) potential collaborations with the National Science Foundation (NSF) NEON Airborne Observation Platform (AOP), ARM Aerial Facility (AAF), and the National Aeronautics and Space Administration (NASA; e.g., LaRC ; Airborne Visible InfraRed Imaging Spectrometer-Next Generation [AVIRIS-NG]), as well as individual PI uncrewed aerial system (UAS) platforms (D. Yang et al. 2022).

Key land-atmosphere interactions science questions for the AMF3-BNF include:

- *What are the primary biotic and atmospheric controls on plant ecophysiology and surface fluxes in the SE U.S. and associated influences on convection?*
- *How does the variation in canopy structure and within-canopy radiation environment influence diurnal to seasonal fluxes of carbon, water, energy, and BVOC?*
- *How do changes in incident shortwave and long-wave radiation and spectral distribution under changing cloud and aerosol regimes impact photosynthesis and transpiration?*
- *What are the dominant controls on the closure of the surface energy budget in the SE U.S. region? How do sub-canopy processes impact the ability to close the energy budget?*
- *What role does surface heterogeneity play in driving the spatial and temporal patterns of surface-atmosphere turbulence, mass, and energy exchanges?*
- *What are the key factors driving the evolution of thermals from the surface to the atmosphere and are current turbulence theories sufficient for boundary-layer modeling?*
- *How does the phenology of the surface vegetation influence the climatology of convection and aerosols in the SE U.S.?*

2.3.1 Forested Tower-Driven Research: A New Opportunity for the ASR/ARM Community

The AMF3-BNF will provide unique opportunities to study LAI across representative land surface endmembers, including a new site within a mature mixed pine-oak forested environment (Section 3) in the SE U.S. The main AMF3-BNF facility will host a forested tower (Section 3.2.2) that is a rare ARM opportunity to directly connect measurements in a forest ecosystem from the soil surface, through the vegetation canopy, and extending above the forest through the ABL by linking sub-canopy, canopy, and ecosystem measurements with radiation and vertical profiling measurements from co-located instrumentation at the AMF3-BNF (specifications and instrument listings as in Section 3.2.2). The team, in coordination with ARM, requested a core suite of instrumentation (Section 3) to characterize the storage and vertical movement of heat, momentum, and water vapor through the canopy as well as to measure the incident and within-canopy radiation regime. The goal was to facilitate state-of-the-art land-atmosphere cloud interactions and coupled aerosol-vegetation research to highlight the "*from the canopy to the clouds*" philosophy of land surface interactions (Sedlar et al. 2022). Opportunities provided by this unique LAI measurement configuration will enable scientists to address current core challenges and uncertainties related to surface-atmosphere coupling (Helbig et al. 2021), multi-scale modeling, and the role of the land surface on ABL state and dynamics in the SE U.S. The design of the AMF3-BNF site also closely approximates the goals and desired configuration of the international GEWEX Land-Atmosphere Feedback Observatory (GLAFO), enabling the AMF3 to participate in international collaborative experiments and syntheses.

2.3.2 Turbulence and the Canopy Environment

The structure, functioning, and composition of the land surface strongly regulate the nature and dynamics of turbulence in the ABL and turbulent flows over space and time, while atmospheric conditions serve as a modulating mechanism for the enhancement or slowing of vertical turbulence (Ghausi et al. 2023). At the same time, the spatial variation in land cover and land-use types can significantly impact local to larger ABL turbulence evolution (e.g., transitions from forest to agriculture to rural and urban environments), while at the fine-scale the three-dimensional canopy environment influences the movement of horizontal and vertical fluxes (Burakowski et al. 2018, De Roo and Mauder 2018, Novick and Katul 2020, Sedlar et al. 2022). Improving our understanding of the surface processes that regulate turbulence is essential to accurately assessing and modeling the transport of heat, moisture, momentum, and chemical species into the boundary layer, which in turn sets the development of dry and moist thermals, and the surface contributions to convective clouds (Bonan 2008, Freedman et al. 2001, Steiner 2020). The challenge in understanding these turbulence processes can be split between (1) within-canopy processes, and (2) characterization of the outer surface layer, considering secondary circulations driven by land cover and transport into the ABL aloft. The AMF3 deployment will investigate the within-canopy turbulence regime and connections with the ambient environment and resulting turbulent transport by measuring the microclimatic conditions within and above the canopy (Section 3.2.2). A combination of distributed micro-meteorological instrumentation deployed vertically in the forest canopy and the use of optical fibers (e.g., distributed temperature sensors [DTS]) will provide fine-scale characterization of momentum fluxes to observe and test turbulence assumptions. Turbulence characterization via tower observations and remote sensing (e.g., Kamoske et al. 2021) will be complemented by modeling of the within-canopy and larger environment using radiative transfer and large-eddy simulations (LES) of the canopy fluxes.

Monin-Obukhov Similarity Theory (MOST) is the most common framework used to represent and model the movement of heat, moisture, and momentum out of the canopy into the ABL (Q. Li et al. 2018). MOST relies on a bulk approach, where horizontal length scales are much larger than the turbulence length scales, and has been traditionally validated for dry, bare soil conditions (Johansson et al. 2001, Novick and Katul 2020, J. Sun et al. 2020). Studies over non-ideal conditions and surface types have identified shortcomings to the MOST approach that have led to issues in closure studies, scaling of fluxes, and driving model-data mismatch under certain conditions (Stiperski and Calaf 2023). The AMF3 deployment will provide an opportunity to study issues driving errors in surface energy closure and MOST assumptions, given the breadth and depth of available measurements (Section 3). Using a combination of vertical radiation, micro-meteorological, and optical fiber measurements, AMF3-BNF will be able to characterize the magnitude and seasonality of common energy closure errors (Foken 2008) (i.e., “missing energy”). These measurements can be paired with vertical soundings and profiling of the ABL to characterize the shape and evolution of turbulent transport and model assumptions. We anticipate modeling studies across a range of spatial and process scales (e.g., canopy, LES, mesoscale) to investigate the basic assumptions of MOST, identify the conditions most appropriate for the use of MOST, and explore alternative assumptions for characterizing the structure of turbulence from the ground to the ABL.

2.3.3 Plant Ecophysiology

The canopy structure, plant physiology, and functioning of terrestrial ecosystems act as primary controls over the fluxes of water, carbon, and energy between the land surface and the atmosphere, while abiotic factors including humidity, soil moisture, temperature, atmospheric chemistry, and radiation strongly mediate plant ecophysiology (Bernacchi et al. 2013, Bonan 2008, Fatichi et al. 2016, F. Li et al. 2023). For example, ambient environmental conditions influence the movement of carbon into plants via photosynthesis and water out of leaves through transpiration via stomatal conductance, processes which are also regulated by the underlying functional properties, seasonality, and three-dimensional structure of the vegetation (Bonan et al. 2021, Niinemets 2007, Rogers et al. 2017). At larger canopy-to-ecosystem scales, atmospheric conditions regulate the cycling of energy and water through sensible and latent heat fluxes, and thus the Bowen ratio. Plant physiology, phenology, environmental conditions, and plant stress can also combine to regulate the emissions of BVOCs (Barth et al. 2005, Steiner 2020), a critical climate control knob in the SE U.S. Similarly, canopy skin temperature and surface energy fluxes are tied to the structure and biophysical properties of the vegetation (e.g., canopy cover, height, leaf area index), including surface albedo (Burakowski et al. 2018, Hoek van Dijke et al. 2020). Vegetation phenology is also a key determinant of the timing and magnitude of surface fluxes and properties of the ABL and convection on longer time scales (Freedman et al. 2001). Given the complex interplay between vegetation and the surrounding environment, the plant ecophysiology underlying the ABL is an important driver of land-atmosphere interactions (Burakowski et al. 2018, Helbig et al. 2021, Novick and Katul 2020).

The AMF3-BNF deployment presents a novel opportunity to leverage the multi-scale observations across the main and supplemental facilities to explore the connection between plant ecophysiological processes and atmospheric conditions at seasonal and inter-annual time scales. Moreover, the deployment will provide exciting opportunities to broaden the scope of ARM science drivers toward addressing science questions critical to the Earth Systems Science (ESS) community, as well as foster coupled surface-atmosphere measurement and modeling activities. Measurements of surface energy, water, and radiative fluxes (using eddy covariance and micrometeorological and radiation measurements) within and above the canopy, together with larger-scale vertical ABL profiling (see Section 3), will offer a unique testbed to investigate the direct and indirect connections between environmental drivers and plant ecophysiology and ecosystem fluxes. Because AMF3 will provide vertical profiling of gas concentrations and fluxes, as well as turbulence measurements (Section 2.3.2) and radiation (Section 2.3.4), it will be possible to investigate the connections between ecophysiology, the 3D canopy environment, and turbulent flows at short (hourly) to long (intra- and inter-annual) time scales under a range of conditions and leaf phenologies. Co-located measurements of aerosol microphysical properties and chemical speciation will yield unprecedented opportunities to investigate the relationships between ecophysiology, emissions of aerosol precursors, and aerosol transformations over these different environmental and seasonal conditions. In addition, the connection between ecophysiology and energy closure can be explored using the range of measurements provided by the AMF3 deployment, including the very high-resolution measurements of vertical turbulence (Section 3.2.2).

Beyond coupled measurement opportunities, the rich data sets collected by AMF3 will also enable new modeling activities, guiding new multi-scale parameterizations and targeting ecophysiological processes. AMF3 will provide many of the critical observations necessary to address process improvements and to evaluate land-surface and LES models (Blyth et al. 2021, Fisher et al. 2018, Fisher and Koven 2020). In addition, we anticipate model experiments focused on evaluating coupled vegetation-aerosol, surface-convection, and two-way feedbacks in coupled modeling frameworks (e.g., E3SM single column, Weather Research and Forecasting (WRF) model coupled with Chemistry [WRF-Chem]) to evaluate and test the strength of surface-atmosphere coupling and feedbacks over seasonal-to-annual timescales, allowing for potential improvements in climate modeling.

2.3.4 Radiation

Atmospheric perturbations to the regional radiative forcing can drive changes in the radiation regime (e.g., direct/diffuse partitioning, increased scattering in photosynthetically active wavelengths) that are likely to affect the functioning of terrestrial ecosystems (Bellouin et al. 2020, Durand et al. 2021, J Li et al. 2022). For example, aerosol scattering can enhance photosynthetic carbon uptake in some terrestrial vegetation types (Zhou et al. 2021), but the controls and strength of this enhancement is not well understood (Bellouin et al. 2020, SJ Cheng et al. 2015, Q Liu et al. 2021, Z Zhang et al. 2021). Changes in local cloud properties may also drive strong responses in surface vegetation that either enhance or modulate surface-atmosphere coupling and moisture fluxes (Xiao et al. 2018). Plant stomata and photosynthesis strongly respond to cloud cover and associated changes in radiation at the surface, yet cloud cover itself is directly rooted in photosynthesis (Vilà-Guerau de Arellano et al. 2014) and the thermals originating from the surface. The vertical distribution of radiation within a vegetation canopy also plays an important role in the distribution of key leaf traits and properties that determine overall ecosystem functioning (Kamoske et al. 2021, Lamour et al. 2023, Niinemets 2007). The strength and spectral characteristics of radiation attenuation in the canopy depends strongly on canopy structure and the properties of absorbing and scattering materials (i.e., leaf, twigs, stems) in the canopy (Serbin and Townsend 2020). Importantly, this attenuation influences the within-canopy radiation regime and regulates other state variables in the canopy impacting surface energy balance including air and skin temperatures as well as fluxes (Bonan et al. 2021). Generally, radiation profiles in the canopy and their impact on whole-ecosystem fluxes are not well quantified, and models that include these processes have significant uncertainties in modeling of surface fluxes and states (e.g., Viskari et al. 2019).

The AMF3-BNF deployment will assess radiation response to changes in clouds and aerosols, as both modify the light both in terms of direct/diffuse as well as spectral distribution (Bellouin et al. 2020). Detailed AMF3 measurements of vertical air temperature, relative humidity, incident radiation (direct/diffuse partitioning), the sub-canopy radiation regime and surface albedo (Section 3.2.2) will inform and evaluate LES and land surface models. These measurements can inform detailed empirical and modeling studies investigating the relationship between incident radiation spectral quantity and quality on surface fluxes and energy cycling, as well as two-way feedback between the surface and atmosphere (Bellouin et al. 2020). Simultaneous surface energy and aerosol measurements can inform model simulations that explore the relationships between plant processes and biogenic VOC emissions and aerosol formation to evaluate the plausibility of a self-regulating aerosol-vegetation feedback.

3.0 AMF3 Sites, Measurements, Strategies, and Partnerships

An AMF3-BNF deployment to northern Alabama can address the science objectives and key questions discussed above. However, placing extended observational networks into this region to accomplish the broader science goals of AMF3 is challenging given the complexity in identifying suitable deployment locations in representative atmospheric conditions, appropriate coverage for land-surface and biodiversity, and other considerations (i.e., restrictions from terrain, stable power, and/or land access). Some practical considerations include how to best position ARM instrumentation within and around the BNF region (e.g., Figure 3) to capture the spatial heterogeneity of the aerosol/cloud/land-surface-use conditions, the calculation of the heat/moisture advective tendencies, and associated budget closures. Additionally, this region is home to several partner collaborative observational networks and natural topological breakpoints interwoven into the overall diverse landscape that will be beneficial to multi-purposed site placement. Table 1 provides a summary of several relevant cloud/aerosol ARM instruments, value-added products (VAPs), and external agency data sets we anticipate as necessary, but not sufficient, for successful research activities in and around the BNF. A current and more comprehensive listing of AMF3 instruments proposed for the M1 (Section 3.2) and supplemental sites (Section 3.3) is on ARM's BNF website.

One unique-to-ARM aspect for this siting plan is our inclusion of an instrumented walk-up tower embedded within the BNF forest and collocated with the main AMF3 site. This siting plan follows previous cornerstone ARM research-driven priorities for multiple supplemental profiling facilities, as well as a full complement of ARM advanced radar, lidar, and aerosol observing systems. Measurement expectations follow the cross-cutting science drivers under aerosol, cloud, and land-atmosphere interaction process themes and require collocated observations at the AMF3 main and its supporting sites. *Note, our definition of "collocation" in the following outline varies depending on whether the measurements are vertical profiling (more stringent geographic requirement), or if these measurements are intended to capture a larger horizontal sampling area (e.g., scanning radar).* For site selection, one goal was to apply best-possible practices to coordinate cloud, aerosol, and land-atmosphere interaction profiling themes. This required ARM placing atmospheric profiling equipment near (e.g., within 1 km) the forested tower or similar sites that enabled the necessary pad/clearing for critical wind profiler sampling, while not significantly disturbing the forest through installing a large clearing or change within the footprint (i.e., an eddy covariance footprint) of the main/supplemental land-atmosphere sampling area biosphere type. Similarly, it was an important consideration that the main site would be situated with a several-kilometer buffer from the edge of the primary forest (approx. 6-10 km, or 2-3 boundary-layer depths) to minimize the impact of land-use gradients to those scales, and within the air mass sampling representative of the primary forest endmember for the area around the AMF3-BNF.

Table 1. Select ARM AMF3 instrumentation, VAPs, and external data sets that the Site Science Team anticipates as critical for a successful BNF deployment.

Instrument or VAP product	Key quantities of interest
Aerosol chemical speciation monitor (ACSM)	Bulk non-refractory aerosol chemical composition
AOS meteorological (AOSMET), SFC met instrumentation (MET)	Atmospheric state
AOS trace gas, CO (AOSTRACE)	Concentrations of trace gases associated with atmospheric chemical processing
Atmospheric Emitted Radiance Interferometer (AERI) Optimal Estimation (AERIoe) algorithm VAP	Liquid-water path, thermodynamic profiling up to 1 km
AOS optical properties, including 3-W nephelometer (NEPH) (scattering); 3-W cloud aerosol and precipitation spectrometer (CAPS) (extinction) 3-W particle soot absorption photometer (PSAP) (absorption) and 7-W aethalometer (AETH) (absorption)	Optical extinction, absorption and scattering coefficients, absorption and scattering Angstrom exponents
AOS scanning mobility particle sizer (SMPS)	Aerosol number size distribution from 10 nm to 500 nm
Ceilometer (CEIL)	Cloud profiling
Cloud condensation nuclei particle counter (CCN)	Potential CCN number concentration at pre-set super-saturations
Condensation particle counter – fine (CPCF)	Number concentration of aerosol larger than 10 nm
Condensation particle counter – ultrafine (CPCU)	Number concentration of aerosol larger than 3 nm
Clouds Optically Gridded by Stereo VAP (COGS)	4D grid of cloudiness for observing sizes, lifetimes, and life cycles of shallow cumulus clouds
C-band Scanning ARM Precipitation Radar (second generation) (CSAPR2)	Precipitation rate, convective life cycle and spatial context, precipitation regime classification
Doppler lidar (DL)	Sub-cloud/clear-sky turbulence, vertical velocity
ECMWF IFS or ERA-5	Model forcing
Eddy correlation flux measurement system (ECOR)	Surface turbulent fluxes of momentum, sensible heat, latent heat, and carbon dioxide
Geostationary Operational Environmental Satellite (GOES-16)	Cloud properties and life cycle
High-resolution aerosol mass spectrometer (HR-AMS)	High-resolution non-refractory aerosol chemical composition
Hygroscopicity tandem differential mobility analyzer (HTDMA)	Size-resolved aerosol hygroscopicity and water uptake
Parsivel laser disdrometer and video disdrometer (LD, VDIS), Laser Disdrometer Quantities VAP (LDQUANTS), Video Disdrometer VAP (VDISQUANTS)	Precipitation rate, raindrop size distributions, precipitation regime classification

Instrument or VAP product	Key quantities of interest
The Ka-band ARM Zenith Radar (KAZR) and Active Remote Sensing of Clouds (ARSCL) VAP	Cloud profiling, cloud life cycle
Micropulse lidar (MPL)	Cloud profiling, aerosol profiling
Microwave radiometer (MWR) and Microwave Radiometer Retrievals VAP (MWRRET)	Precipitable water vapor, liquid water content
NOAA Next-Generation Weather Radar (NEXRAD)	Precipitation rate, raindrop size distributions, precipitation regime classification
Nephelometer (NEPH)	Aerosol total scattering at ambient conditions and at "dry" conditions
Organic Aerosol Component (OACOMP) VAP	Organic aerosol mass concentration by organic aerosol type from the ACSM
Proton transfer reaction-mass spectrometer (PTR-MS)	VOC concentration
Radar wind profiler (RWP)	Convective vertical velocity, precipitation profiling and regime classification, wind shear and PBL height
Radiosondes (SONDE) and Interpolated Sonde VAP (INTERPSONDE)	Thermodynamic parameters Atmospheric state, model forcing
Raman lidar (RL)	Profiling to include the higher-order moments of water vapor, water vapor flux
Scanning ARM Cloud Radar (SACR)	Cloud properties and life cycle
Single-particle soot photometer (SP2)	Refractory black carbon (rBC) mass concentration, size distribution, and mixing state (particle-resolved mass ratio of coating/rBC core)
Sky radiometers (SKYRAD)	Downwelling broadband radiation (direct, diffuse, global)
Tethered balloon system (TBS)	Atmospheric profiling
Total sky imager (TSI)	Cloud profiling, cloud life cycle
Uncrewed aerial system (UAS)	Atmospheric profiling
Ultra-high-sensitivity aerosol spectrometer (UHSAS)	Aerosol size distribution from 100 nm to 1 micrometer
SCM Forcing Data from the Constrained Variational Analysis VAP (VARANAL)	Continuous model forcing data set
Visible Infrared Solar-Infrared Split Window Technique (VISST)	Satellite-based retrievals of cloud and radiation properties

3.1 Duration and Seasonal Expectations

A core aspect of the AMF3-BNF deployment is its expectation for longer-term (~five-year) observations to help address potential local, seasonal to inter-annual variability concerns that often limit the characterization of local to larger-scale cloud, aerosol, and coupled land-atmosphere processes or phenomena. Alabama experiences a range of cloud conditions throughout the year, ranging from summertime shallow-to-deep isolated convection to larger-scale synoptic intrusions in transitional periods associated with organized and severe thunderstorms. Similarly, the observational domain (within BNF and anticipated supplemental site boundaries) is also characterized by seasonality in aerosol composition and aerosol precursor emissions, particle water uptake, and biomass burning (prescribed and incidental). The region contains a wide range of land surface/vegetation types and uses (Figure 5) that vary significantly in their surface biophysical (height, albedo, leaf area index, Figure 6) and biochemical (VOC, soil nitrogen) properties. This likely drives strong spatiotemporal variation in surface fluxes across the domain that may strongly influence vegetation-aerosol and cloud coupling, or seasonality in shallow convection and precipitation.

3.2 AMF3 Main Site (M1) Deployment

The measurement recommendations for the AMF3 and its placement in the BNF are consistent with the deployment of instruments as outlined by the original AMF3 planning documentation and AMF3 facilities therein. *This section of the Science Plan covers only the key main site measurement expectations that were not explicitly detailed by those previous documents*. For the sections that follow, we focus on new instrument requests, or instances where there was ambiguity in the potential options or operations to meet measurement requirements. In Figure 7, we plot a preliminary layout for the Main Facility (M1, in ARM's AMF terminology) site and its associated instrument layouts at the USFS District Ranger Office at the Black Warrior Work Center (BWWC) in the BNF. This figure also provides locations of the planned collocated tower facility and other landmarks within the BNF.

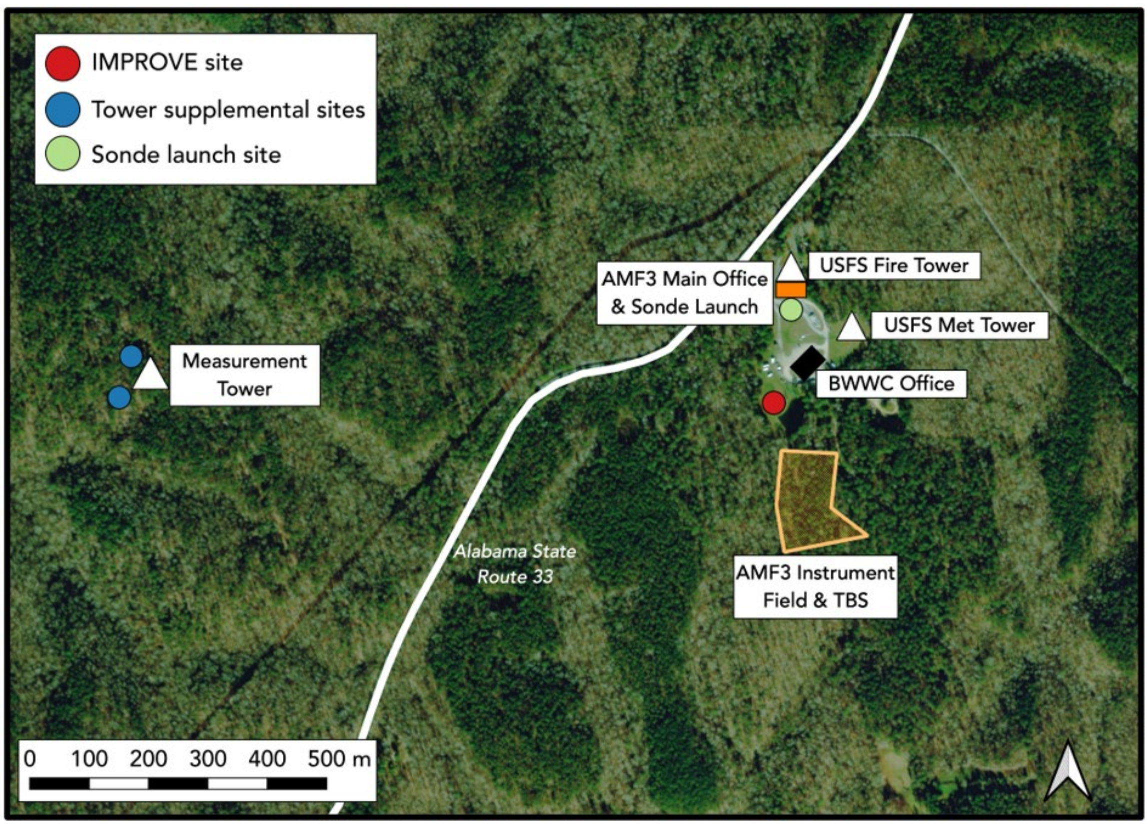

Figure 7. The proposed AMF3-BNF site layout including the location of the main M1 facility and offices, radiosonde launch location, instrument field, TBS launch area, and its placement relative to the instrumented walk-up tower site west of Alabama State Route 33.

3.2.1 BNF Main Site (M1) Advanced Measurement Recommendations

Although the current AMF3 and its typical baseline capabilities that will accompany its relocation to the SE U.S. are suitable to investigate several of the regional science drivers, inclusion of select advanced instrumentation may dramatically accelerate community progress towards achieving such goals over a multi-year BNF deployment. For the M1 site, we offer recommendations for several advanced instruments and measurements that we believe are critical to the success of AMF3-BNF efforts.

Advanced Lidar

A key ARM commitment to the AMF3-BNF was the ability to deploy advanced lidars at the main facility. Both the Raman lidar (RL) and the high-spectral-resolution lidar (HSRL) have been requested for this campaign. Justification for the advanced lidar in these regions includes the ability to characterize: (i) water vapor entrainment at the top of the convective boundary layer (CBL) (water vapor budget), collocated with a Doppler lidar (DL) to derive water vapor flux profiles; (ii) profiles of aerosol backscatter, aerosol extinction, and aerosol depolarization; (iii) computations for water vapor variance and skewness profiles; and (iv) aerosol hygroscopicity at ambient conditions (well-mixed CBL). A DL is also expected at the main site to complement the other advanced lidars and provides horizontal wind profiles and turbulence profiles (via variance and skewness of the vertical motions).

Aerosol and Trace Gases

Requested resources for additional aerosol and trace gas instrumentation beyond that of a standard AMF3 AMF and/or AOS deployment can be organized by planned operational modes: long-term/continuous versus IOP (intensive operational period). Under an IOP basis, a proton transfer reaction-mass spectrometer (PTR-MS) is requested for the measurement of high-time-resolution speciated VOCs, with potential long-term sampling modes (e.g., cartridge-based VOC sampling) contingent on projected operational burdens. A trace gas monitor for SO_2 and NOx for characterizing anthropogenic influence is requested for long-term/continuous sampling. Additionally, measurements of OCS (carbonyl sulfide) are requested to fill a critical measurement gap related to the sulfur cycle, and provide an important constraint on partitioning ecosystem respiration and carbon uptake (Maseyk et al. 2014, F Yang et al. 2018). Under an IOP basis (see Section 3.5), the following instruments are requested: HR-AMS/filter (on-line/offline chemical composition), and CIMS (chemical ionization mass spectrometer for aerosol precursors – e.g., sulfuric acid, amines/ammonia, terpene ozonolysis products). Given the expected important contribution of biological aerosol sources in the region (e.g., pollen, fungus, bacteria), a biological aerosol monitor (e.g., WIBS – wideband integrated bioaerosol sensor) is requested to capture the seasonality in biological aerosol sources, as well as INP filter-based sampling. An HTDMA and humidigraph are also requested to characterize the impact and seasonality of sub-saturated water uptake on aerosol optical properties and radiative forcing.

Multi-Sensor Atmospheric Thermodynamic Profiling

The BNF anticipates a heavily instrumented site amenable for detailed boundary-layer profiling. The profiling aspects (multi-parameter) for these sites may be accomplished through frequent radiosonde launches (standard ARM 4/day, with possible IOP changes to higher frequency), and a variety of instrument pairings. The main AMF3 site would prioritize advanced lidar capabilities, as well as atmospheric emitted radiance interferometers (AERI) or equivalent to profile temperature (T) and relative humidity (RH), as well as estimates for liquid water path < 60 g/m^2 with reasonable quality. The main site would host the 2- or 3-channel microwave radiometers (MWR)s to provide a pathway for liquid water path (LWP) sampling over the entire range of LWP. Wind profiling at the main site may be accomplished with the DL and supported by the radar wind profiler (RWP). The latter allows profiling of winds above the cloud layer and offers value in precipitating conditions for convective core sampling. Finally, micropulse lidar (MPL) and ceilometer (CEIL) are standard ARM instruments for profiling boundary-layer and cloud properties, serving as key inputs to several ARM VAPs (i.e., ARSCL, AERIoe).

Cloud/Precipitation Sampling and Imaging (Radar, Camera, Column)

The expectations for M1 are consistent with standard ARM AMF3 deployments for the Ka-band ARM Zenith Radar (a newer, second-generation KAZR has been recommended) and the profiling sensors discussed above. In addition, there is strong community support for column and spatial cloud imaging equipment at the main facility to include total sky imager (TSI) or equivalent, with a main emphasis on stereo camera (STEREOCAM) options as available. Tower facilities around the main site (including a nearby fire-tower at the BWWC and the walk-up tower described in Section 3.2.2) may provide adequate options for stereo camera placement with ARM mentor support (e.g., Figure 8). These STEREOCAM possibilities are an important community request because they provide high temporal/spatial properties of the cloud boundaries (i.e., cloud base, top with time, proxies for vertical motions and/or entrainment), fractional coverage, and evolution for model evaluation that is typically unavailable from satellite or scanning radar that might otherwise overlook the BNF M1. Additional cloud/precipitation sampling collocated with the nearby walk-up tower will be discussed in Section 3.2.2.

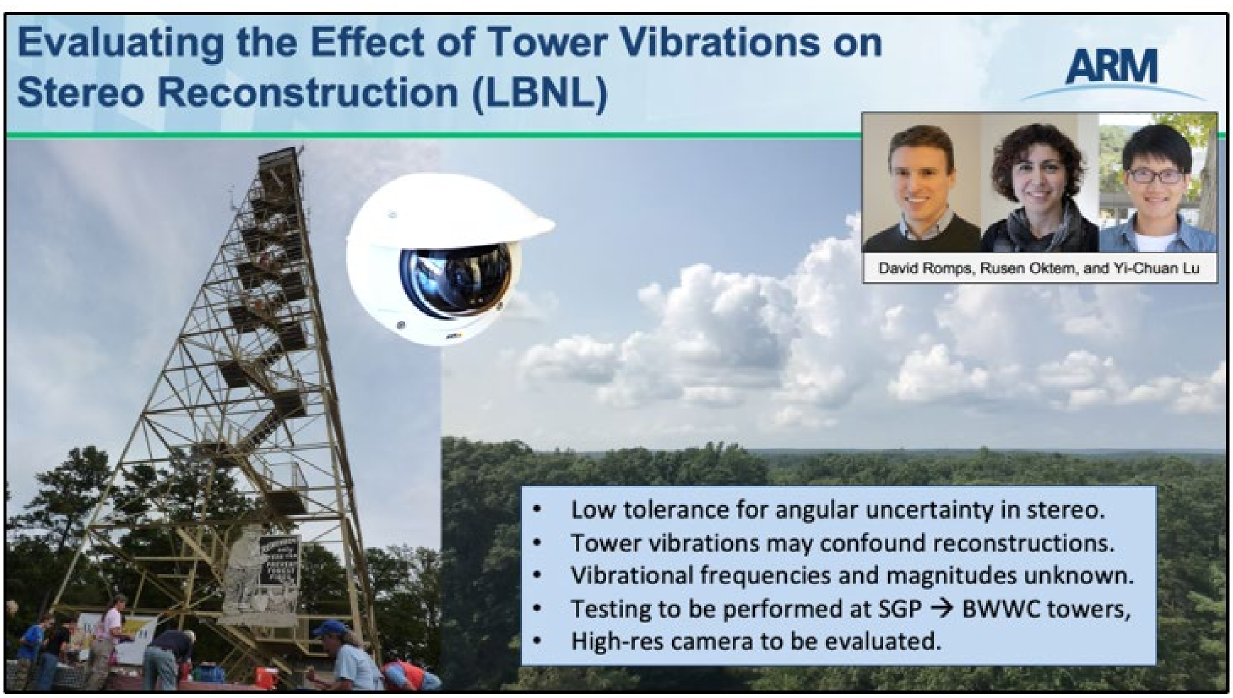

Figure 8. An example slide presented at the 2022 ASR/ARM PI Meeting AMF3 breakout session on pre-deployment stereo camera activities spearheaded by the Science Team and ARM mentors.

PI-Guest Deployment Supporting Facilities

Additionally, a Guest Instrument Facility (GIF) and guest AOS are requested to support aerosol IOPs and PI-guest deployments (as also in Section 3.5.2). The guest AOS is recommended to have an aerosol inlet identical to the AOS03 with supporting pumps and blowers, along with rack space for instrument installation. The GIF is requested to provide sufficient workspace (e.g., for sample preparation, instrument calibration), inlets (e.g., shared/individual, wall/ceiling penetrations), and supporting measurement infrastructure (e.g., UPS, 100A electrical service) in support of PI-guest deployments.

Land-Atmosphere Interactions – Advanced Instruments

The team anticipates that most micrometeorology, surface energy exchange and eddy covariance, soil properties, and other M1 collocated main site (primary instrument field) requirements can be met with the standard AMF3 deployment. Advanced or new-to-ARM LAI instrumentation recommendations are primarily associated with the forested walk-up tower facility that is immediately adjacent to, yet collocated with, the M1 site with respect to select larger-scale thermodynamic, cloud, and aerosol capabilities afforded by the AMF, its instruments, and AOS (discussed in more detail in Section 3.2.2).

The ARM Tethered Balloon System (TBS) and Uncrewed Aerial System (UAS)

ARM Aerial Facility (AAF) assets such as the ARM TBS and UAS, or similar partner facilities, may provide critical insights as emerging technologies to observe the spatial (vertical and horizontal) distribution of atmospheric properties over heterogeneous land-surface types. Having air space or line of sight for TBS or UAS operations is an important consideration for their availability to achieve the science drivers around the M1 location. The AMF3-BNF is associated with an airspace that should allow for low altitude (≤ 400–1200 ft AGL, daytime, line-of-sight) small UAS (sUAS) flights over the M1 location. For example, these operations may be allowable under the blanket DOE Certificate of Authorization (COA), or by partners through Part 107 certification. For UAS or activities outside of the bounds of the COA or Part 107, we expect that the BNF airspace should allow for supplemental COAs to enable non-line-of-site, high-altitude, and nighttime operations (where necessary/appropriate).

For example, the TBS is requested by the Site Science Team and its drivers to provide vertically resolved measurements of relevant aerosol properties (e.g., number size distribution, optical properties, chemical composition, ice nucleating potential) and atmospheric state (e.g., T, RH, pressure [P], 3D wind speed). At the time of this writing, the Site Science Team, in discussion with ARM, anticipates M1 TBS or UAS efforts to operate under IOP and/or guest instrument requests in FY2025 (as in Section 3.5.2). Appropriate ARM support requests will accompany proposed guest deployments. Measurements of aerosol chemical composition will be accomplished via deployment of the EMSL Science and Technology Advisory Committee (STAC) platform for in situ sample collection followed by offline analysis using EMSL microscopy and mass spectrometry instrumentation. The following ARM TBS resources are requested: portable optical particle spectrometer (POPS; aerosol size distribution from 140 nm to 3 um), the TSI 3007 condensation particle counter (CPC; total aerosol number concentration larger than 10 nm), the microAeth (black carbon optical properties), IcePuck (ice particle nucleating potential), DTS, cup anemometers, 3D sonic anemometer, and iMet RSB (radiosonde) and XQ2 (UAS) sensors (T, RH, P).

3.2.2 BNF Walk-Up Tower Recommendations

The Site Science Team made a series of suggestions and recommendations for the deployment of an accessible, walk-up tower, extending above the top of the vegetation canopy, to be sited at the AMF3-BNF M1 site within a representative forest and spatially collocated with the larger suite of AMF3 measurements. The purpose of this walk-up instrument tower is to conduct detailed studies of land-atmosphere interactions and two-way feedbacks between surface vegetation, aerosols, and cloud processes. In addition, the tower will enable model-data integration studies of surface contributions to atmospheric dynamics and high-resolution and multi-scale modeling, and be accessible to facilitate easier deployment of guest instrumentation. The team recommended that the tower provide detailed vertical (multi-level) measurements of turbulent fluxes, canopy storage of trace gases, heat and moisture, short- and long-wave radiation, and surface temperature and albedo. The recommendations were also for the installation of instrumentation to provide very high-resolution vertical heat and momentum measurements to facilitate evaluation of turbulence assumptions within vegetation canopies. Finally, the team recommended that the tower site include at least two sub-canopy micrometeorology and flux towers to capture the within-canopy turbulence regime, and that these locations, and the main tower, measure soil moisture, temperature, and heat fluxes at multiple soil depths.

BNF M1 Tower Siting, Placement, and Basic Accessibility

The core LAI science objectives, as well as the cross-cutting coupled science objectives of the SE U.S. deployment, depend on a well-sited and instrumented tower(s) within select vegetation types (e.g., deciduous broadleaf and evergreen needle-leaf/pine forest, plantation, managed agriculture). Standard surface measurement and tower requirements are based on typical micrometeorological and eddy covariance deployments (Baldocchi 2003). Below, we summarize our basic tower requirement philosophy, as associated with the team-recommended standard tower facility for the forested BNF M1 region, with the primary tower ideally collocated near that AMF3 M1 facility:

- *Tower Height*: Extending above the mean canopy height into the surface roughness layer; For the M1 site in the BNF, canopy height is approximately 25 meters (Figure 9).
- *Accessible*: Although a walk-up tower is preferred, other reasonable tower designs (e.g., telescoping, tipping) accessible for instrument maintenance, replacement, or short-term instrument deployments are recommended.
- *Sturdy*: Some measurements will be impacted by tower movement in wind.
- *Vertical Installation of Instrumentation (Multiple Levels)*: This may include booms extending out/away from the tower, as also to place instruments above the vegetation canopy and/or away from any gap around the base of the tower.

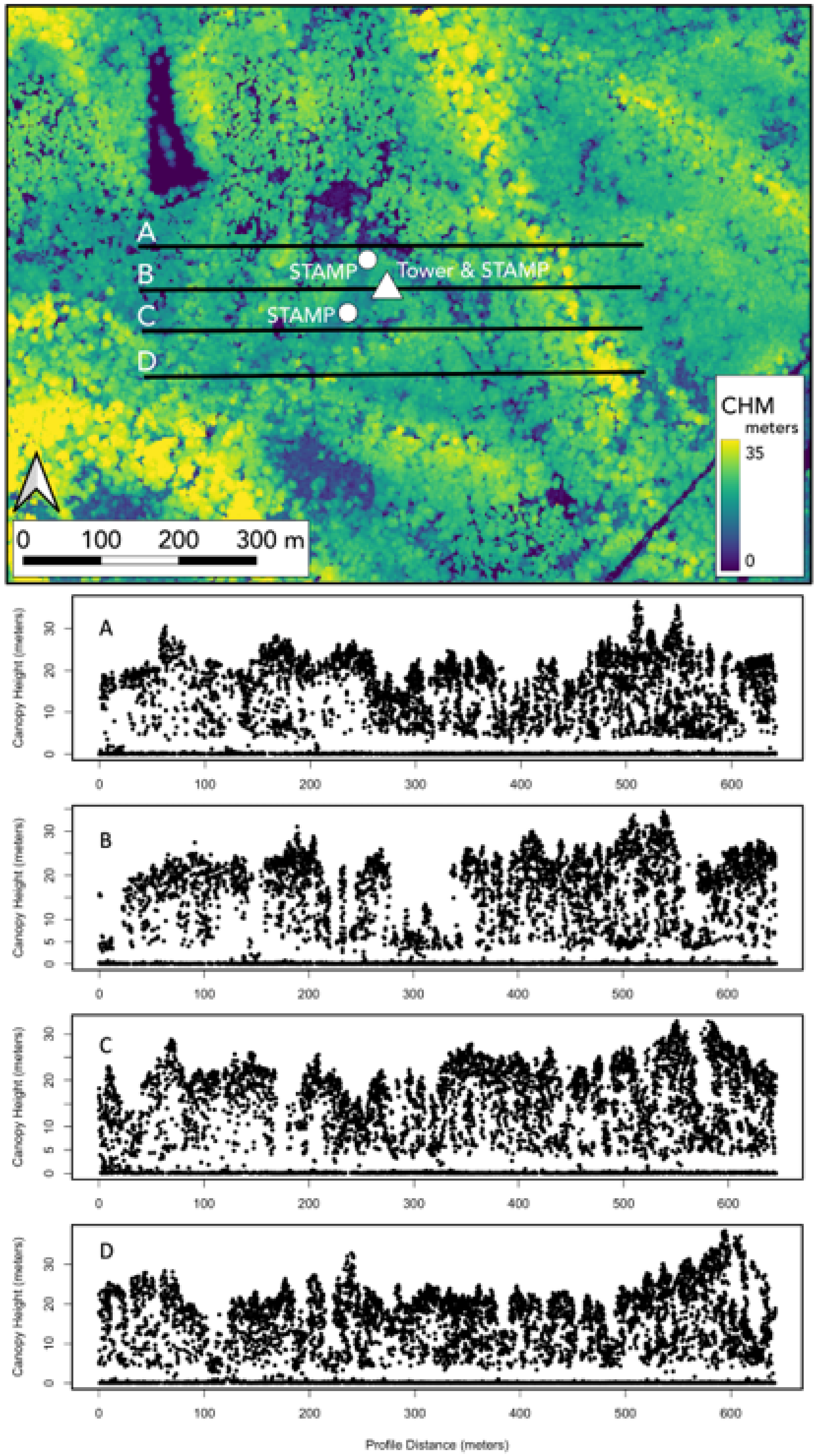

Figure 9. Suggested spatial layout of the AMF3-BNF main facility walk-up tower and associated under-canopy tower and soil temperature and moisture profiles (STAMP) locations overlaid by the 2012 lidar-derived vegetation height. Example two-dimensional canopy profiles.

In addition to the physical requirements for a standard tower in the BNF discussed above, M1 tower siting implied other considerations that included:

- Tower located within a reasonably homogenous forest; Sufficient fetch containing similar and representative vegetation and/or without breaks;
- Tower sited sufficiently far from undesired anthropogenic emission sources;
- Tower sited in non-complex terrain;
- Tower sited within a mature forest, e.g., >30 years for non-plantation;
- Tower sited in a low-to-no management area.

Overall, the Site Science Team stressed that *tower siting and its physical characteristics or measurement capabilities are critically coupled and not orthogonal*. For a regional example, the existing NEON TALL tower (https://www.neonscience.org/field-sites/tall) is located in an evergreen needle-leaf forest with a mean canopy height of 25 meters and a current tower height of 35 meters. Common micrometeorology and eddy covariance configurations include four to six measurement levels, typically focused on capturing vertical profiles of radiation, wind, trace gas concentration, T, RH, and P.

Aerosol Flux System

The atmosphere and biosphere are linked via vertical fluxes of momentum, sensible/latent heat, and fluxes of atmospheric trace gases and aerosol. The vertical exchange between the land surface and the atmospheric boundary layer is established mainly through turbulence, which is complex and challenging to quantify. As part of the AMF3 tower measurements, we request the measurement of aerosol fluxes at multiple heights (top of tower, above canopy, below canopy, 10 meter). Measurements of high-time-resolution aerosol concentrations will be combined with 3D-wind, air temperature, and humidity observations from the facility-specific multi-level meteorological instrumentation (TOWERMET) system to produce an aerosol flux product. The calculation of aerosol turbulent fluxes will follow an eddy covariance approach using the TOWERMET measurements combined with a condensation particle counter (CPC) at each TOWERMET level operating at potentially 10 or 1HZ with the appropriate cut-off size (e.g., 10 nanometers), flow rate (0.3 - 1.5 lpm), counting statistics (total flow versus core-extracted flow sampling), and flow-control (internal versus external pump).

Tower PI-Guest Deployment Supporting Facilities

The Site Science Team recommends that the AMF3-BNF walk-up tower facility provide adequate support (e.g., infrastructure, power, internet) for guest instrumentation to be deployed above and within the forest canopy. This should include platforms and other physical infrastructure for instrument installation at different levels on the tower. The team anticipates that most of these requests will be handled by ARM through guest instrument or small IOP campaign requests (for more information, Section 3.5.2).

Distributed Temperature Sensing (DTS)

A core focus of the AMF3-BNF deployment is to investigate the relationships between surface properties and boundary-layer turbulent fluxes and dynamics over space and time. The horizontal and vertical structure of vegetation canopies (Figure 9), and their function over the day and seasonally, strongly regulate the characteristics and evolution of boundary-layer thermals. Understanding the regulation of turbulent fluxes over the short (hourly) and long term (monthly, annually) is critical for characterizing the evolution of the ABL but is also a critical knowledge gap in models focused on simulating the role of the land surface on local weather and regional climate. To improve our understanding of the role of land surface on turbulent fluxes, the Site Science Team recommends the deployment of optical fiber DTS equipment (Y Cheng et al. 2017, Stoy et al. 2019). We recommend the installation of the DTS along the vertical axis of the walk-up tower to provide very high-spatiotemporal-resolution measurements of heat and momentum to capture finer-scale evolution of thermals from the surface to the atmosphere. Additional installations of a DTS system around the tower site in the horizontal dimension is also recommended, but likely supported by an IOP or PI-driven opportunity.

Vertical Profiling of Within-Canopy CO_2 and Water Vapor Storage

For many taller vegetated systems (e.g., forests) the storage of heat, CO_2, and water vapor in the canopy can occur under stable (low-wind) conditions (Nicolini et al. 2018, K Xu et al. 2019) and lead to biases in the calculation of vertical flux gradients and ecosystem-scale flux quantities (e.g., net ecosystem exchange, NEE). Correcting for this within-canopy storage flux is often necessary to minimize flux and energy closure errors and uncertainties, and the most direct means for correcting for storage is to directly measure the storage terms using a profiling system (Montagnani et al. 2018, Nicolini et al. 2018, K Xu et al. 2019). The team recommends the deployment of a storage profiling system (e.g., Campbell Scientific AP200, https://www.campbellsci.com/ap200) to enable enhancement flux QA/QC and correction of canopy storage on ecosystem flux calculations.

Vertical Profiling of Greenhouse Gases

The concentration and distribution of greenhouse gases (GHGs) in the atmosphere is a leading driver of anthropogenic climate change. In the southeastern U.S., sources of GHGs include human activities, management of food and fiber resources, and natural ecosystem processes. To meet the scientific needs for the measurement and characterization of GHGs and the ratio of atmospheric isotopes of CO_2 ($12CO_2/13CO_2$), we recommend that the precision gas system isotope analyzer (PGSISO) be deployed on the AMF3-BNF forested walk-up tower. We recommend that PGSISO measurement inlets be installed at multiple vertical levels along the tower, including the tower top, above and below the mean forest canopy height, and near the ground surface (~10m).

Multi-level Fluxes and Sub-Canopy Micrometeorology

As discussed in Section 2.3, the measurement of seasonal turbulent fluxes and exchanges of momentum, mass and energy between the land surface and the atmosphere is an essential measurement for studying land-atmosphere interactions, coupling, and two-way feedbacks with the atmosphere. For plant canopies, the three-dimensional structure and horizontal and vertical variation in photosynthetic functioning regulate these fluxes, which also vary over the diel to seasonal timescales in response to ambient environmental conditions. The most common approach to measure the exchanges of CO_2, water vapor, and energy (latent and sensible heat fluxes) between the land surface and the atmosphere is the eddy covariance (EC) approach (Baldocchi 2020). To address core LAI science goals of AMF3, we request the installation of EC equipment on the AMF3-BNF tower at multiple vertical heights, including the tower top, above the mean canopy height (> 30 m), and below the canopy (e.g., 15m). We recommend either the ARM eddy correlation flux measurement system (ECOR) or carbon dioxide flux measurement system (CO2FLX), possibly combined with AmeriFlux assets, for these measurements and that the instrument heights be paired with heights for the TOWERMET, photosynthetically active radiation (PAR)/radiation system, and requested aerosol flux (see Aerosol Flux System above) systems to provide co-located datastreams on the tower. In addition, we recommend the deployment of a methane flux instrument co-located with the EC instruments at the tower top (~43m) to capture the ecosystem-scale CH_4 dynamics from the forest site.

Along with the vertical EC measurements, we recommend the placement of at least two sub-canopy towers at least 40 meters from the main tower and separated by at least 100 meters to measure the sub-canopy fluxes with EC instrumentation placed at least 10 meters above the local ground surface. These under-canopy towers should be co-located with surface/subsurface energy and water measurements (see Soil Surface and Below-Ground Characterization of Heat and Moisture section).

Surface Skin Temperature

The within-day to seasonal variation in surface skin radiometric temperature is a key component of the surface energy balance and an indicator of vegetation function, stress, and transpiration rates. Within a forested canopy, the different components of the vegetation (leaves, stems, twigs) and ground surface (soil, litter layer) create strong gradients in surface temperatures that contribute to the overall within-canopy temperature environment and influence thermals. The team recommends the deployment of infrared radiometers to quantify the variation in canopy and sub-canopy surface temperatures at multiple tower levels. At a minimum, these levels should include the top or near the top of the tower to observe the canopy surface and within the canopy below the average height of the canopy (~25 meters, Figure 9).

Canopy Phenology

The seasonal phenology of vegetation is strongly regulated by ambient environmental conditions and is a key driver of surface fluxes (Richardson et al. 2009). Because the AMF3 deployment will provide longer-term measurements (~five years) and will be able to characterize seasonal and inter-annual conditions, the Site Science Team recommends that the tower site near M1, and associated towers at supplement sites (Figure 3, Section 3.3), provide measurements of canopy (and understory, where applicable) phenology. This requirement can be satisfied using at least one optical RGB camera located at the top of the tower pointing at the canopy surface at a fixed or repeatedly measured location that is captured during multiple time points each day and over the year (Moon et al. 2022). Where available, measurements of incident and under-canopy radiation or PAR (see below) would also allow for the characterization of changes in vegetation phenology (Ahl et al. 2006, Serbin et al. 2009) that can be linked in other measurements, including EC fluxes.

Radiation Profiling, Leaf Area Index, and the Fraction of Absorbed Photosynthetically Active Radiation

Models that simulate surface fluxes from vegetation canopies include a mathematical representation of the within-canopy environment to partition the direct/diffuse radiation fluxes that drive canopy photosynthesis, transpiration, and energy fluxes. These representations can be simple 1D big-leaf models, a two-big-leaf representation of sun and shaded leaf fractions, and a more complicated multilayer canopy (Bonan et al. 2021). The characterization of the vertical distribution of radiation, in particular PAR, is important for quantifying the degree of shortwave radiation absorption by the vegetation and modeling of forest ecosystems. The Site Science Team recommends the installation of radiation profiling equipment at the tower to capture the distribution of transmitted, reflected, and absorbed radiation to characterize the seasonal variation in the radiation regime, leaf area index, and fraction of absorbed PAR (fPAR). We recommend that radiation and PAR sensors be installed at the top of the tower to measure the downwelling and upwelling (off the canopy surface) direct/diffuse radiation fluxes, and multiple locations below the upper canopy surface to characterize the vertical radiation profile (e.g., at 15, 10, 4 meters, and at ground surface). Additional instrumentation targeting the full shortwave (i.e. 0.3 to 2.5 microns) spectral properties of the downwelling and upwelling direct and diffuse radiation at the top and under the canopy is also recommended (e.g., Delta-T SPN1 pyranometer https://delta-t.co.uk/product/spn1/).

Soil Surface and Below-Ground Characterization of Heat and Moisture

The movement of heat and moisture into and out of the soil is a key component to the overall surface energy balance and ecosystem water cycle. A goal of AMF3 deployment will be to understand the drivers of variation in surface energy balance and the factors that influence the closure of water and energy cycling at the measurement sites. To facilitate science objectives associated with surface energy balance, we request at least two forested locations around the main tower to measure soil evaporation, temperature, soil moisture, and soil heat flux. We require measurements at depth (e.g., 5, 10, 15, 30, 50 cm), but specific depths will depend on soil, site, bedrock depth, and other characteristics that will be determined after the final site has been selected. Core instrumentation to deploy for these locations would include the ARM surface energy balance system (SEBS) and STAMP systems. Additionally, quantifying the amount and size distribution of precipitation reaching the canopy top and the rate of water reaching soil surface should be possible using equipment such as rain gauges and disdrometers positioned above and below the canopy.

3.3 AMF3-BNF Supplemental Sites

A key Site Science Team and community recommendation was for the embedding of the AMF3 M1 facility, its tower, and adjacent capabilities, within a network of supplemental profiling and atmospheric sampling facilities. *One strong recommendation was for having at minimum three non-collinear (mesoscale) facilities distributed throughout the wider N. AL region*. Such an extended network of two or more supplemental sites (along with the M1 site) enables improved sampling of the cloud field, and the calculation of the heat/moisture advective tendencies and the spatial variability in aerosol and land-surface conditions (i.e., including ARM's larger-scale VARANAL VAPs). For example, one hypothesis on why convective clouds (especially the locally driven shallow cumulus during the SE U.S. warmer season) are poorly captured by current models is related to the significant spatial and vertical heterogeneity in water vapor, driven by the spatial variability in the surface latent heat fluxes and terrain height that accentuates this variability. These issues may be exacerbated in SE U.S. summertime conditions when winds are calm and the forcing is weak. *One recommended configuration for profiling sites would be placement of a triangle of sites, with the center of this triangle at the M1 AMF3 facility.* For traditional ARM larger-scale variational forcing data set needs, these sites should be spaced approximately 60 km (flexible, though spacing requested within 40-80 km) apart on edge, similar to the ARM SGP extended facility (Wagner et al. 2022). Initial location(s) meeting an appropriate set of baseline criteria have been identified with community feedback (e.g., Figure 3); however, final decisions will be left to ARM, potentially adjusted to promote additional biodiversity/land-use variety and/or in response to other practical considerations.

As highlighted above, one motivation for advancing ARM's supplemental site capabilities follows from Wagner et al. (2022) and similar methods to measure profiles of water vapor and temperature advection from distributed networks that deploy AERIs and Doppler lidars as recommended for this deployment. ARM profiling sites would define a polygon with one site at each vertex, and the ARM observations would be used to estimate the line integral of the u and v winds and the advected scalars (e.g., heat, humidity, and possibly chemical compounds) around that polygon. Green's theorem can be used to relate the spatial derivatives of u, v, and the scalars in the x and y directions; the advection, deformation, divergence, and vorticity can then be determined from those values. These techniques have previously shown excellent agreement with direct calculations of advection when applied to convective-scale model output, and because this technique can be used to calculate divergence, large-scale subsidence over the target region can also be quantified. With the advective tendency properly estimated, and the surface fluxes observed, a better estimate of the entrainment fluxes for various scalars can be given, as well as the covariability of these species, even in a rapidly evolving boundary layer.

This section documents the key measurement requirements and instrumentation associated with the recommended supplemental sites. Regional partners and/or additional ARM IOP efforts may also be leveraged to provide complementary equipment (guest deployments, or IOP otherwise) that enables enhanced profiling capabilities. Our definition of supplemental sites follows that employed by ARM and may also include additional locations to accommodate scanning ARM radar assets that cannot be placed within the BNF proper owing to tree/canopy (approximately 20-25m), terrain blockage and other practical considerations (structures, land agreements). Optimal radar placement for AMF3 scientific priorities under convective cloud drivers emphasizes radar sites at flexible distances (i.e., often 10 km to 50 km) from the main facility to enable clutter-free profiling over the site and improved coordination with regional radars (including multi-Doppler scanning capability with appropriate radar-to-radar baselines).

3.3.1 Supplemental Site(s) and Supplemental Site Profiling Network

Supplemental Site Aerosol Measurements: Distributed Measurement Network

Within a global climate grid cell, aerosols exhibit high spatial variability due to their disparate sources, short atmospheric lifetimes, strong coupling to the land-surface heterogeneity via surface heat, mass, and momentum fluxes, and the nonlinear, interdependent physical and chemical processes that control their properties. Land-surface controls on aerosol sources (e.g., vegetative BVOC emissions, anthropogenic SO_2/H_2SO_4 emissions, biomass burning), sinks (e.g., wet/dry deposition), and transformations (e.g., aerosol uptake of atmospheric water vapor) tend to vary significantly over short distances, leading to complex interactions between atmospheric aerosol evolution and the dominant spatial patterns of relevant surface fluxes. Aerosol advection further obscures characterization of land-surface aerosol controls due to simultaneous mixing and aerosol processing during transport. Land-surface controls on aerosol present a significant observational and modeling challenge, limiting our ability to understand and predict aerosol effects on radiation, precipitation, and thus weather and climate in heterogeneous regions, as exemplified by the agricultural, forest, rural, and urban atmospheric environments and topography impacting the deployment of the AMF3 in N. AL. Historically, complex measurements of the range of aerosol properties have been made at a single point, which informs our understanding of the relationship among aerosol physical, chemical, and optical properties.

To address the current knowledge gaps, however, spatially distributed aerosol measurements are critically needed to understand land-surface controls on the variability in aerosol-climate impacts, particularly in the Southeast U.S. While heavily instrumented "point" measurements (e.g., AOS) have proven immensely useful for process-level science, they may not necessarily be representative of the larger atmospheric environment. We request the development of an aerosol measurement network that meets both the measurement requirements needed to characterize aerosol-climate impacts, as well as the operational requirements needed to support a lower-cost, lower-complexity system. Below are measurement and operational recommendations for a single node of such a network: aerosol size distribution (10 nanometers-35 microns), aerosol number concentration (> 10 nanometers), CCN-active concentration (~ 0.1-2% super-saturation), aerosol optical properties (e.g., absorption, black carbon), aerosol chemical composition (organic/inorganic speciation), trace gases (e.g., CO, CO_2, NO, NO_2, O3, SO_2), and meteorology (T/P/RH, wind speed/direction).

Supplemental Site Thermodynamic and Cloud Profiling

The cloud profiling aspects (multi-parameter) for AMF3 supplemental sites may be accomplished through a variety of subset instrument pairings, as introduced in M1 site sections and tables previously. Primary science drivers for this campaign give preference to multiple instances of key instruments and profiling for addressing spatial heterogeneity, including characterizing the spatial variability in atmospheric state, turbulence, liquid water path, and its impact on cloud properties, as a function of surface turbulent fluxes. This multi-instrument approach provides improved range and reduced uncertainty in key measurements. We recommend supplemental locations having the following profiling equipment:

- Atmospheric emitted radiance interferometer (AERI);
- Doppler lidar (DL);
- Disdrometer, preferably laser disdrometer (LDIS) or video disdrometer (VDIS);
- Infrared thermometer (IRT);
- Surface meteorology systems (MET) with tipping-bucket rain gauge (TBRG);
- Multifilter rotating shadowband radiometer (MFRSR);
- Microwave radiometer (MWR) – 3-channel;
- Radar wind profiler (RWP) – Contingent placement, to support deep convective themes;
- Total sky imager (TSI) or equivalent camera options.

Supplemental Site Land-Atmosphere Profiling

Key land-atmosphere measurements at the supplemental facilities are highly contingent on potential AMF3 activities that may include supplemental tower siting, collocation, and additional coordination. These measurement recommendations should consider flexible placement of a subset of ARM instruments to capture spatial heterogeneity, as well as a diverse set of underlying plant functional types. As with M1 and cross-coupling with its adjacent tower facility capabilities, potential options may also include deploying select measurements currently unavailable in ARM. Overall, one emphasis is for these sites to carry at minimum a modest set of measurements for micrometeorology, eddy covariance (at minimum, surface energy fluxes), and the boundary layer – all quantities critical to land-atmosphere drivers. ARM instruments of importance to supplemental site measurements that are currently known include:

- Eddy correlation flux measurement system (ECOR);
- Surface energy balance system (SEBS);
- Soil temperature and moisture profiles (STAMP);
- Solar infrared radiation station (SIRS).

Additional instrumentation that may provide benefit at the supplement sites also includes:

- Infrared radiometers, to measure surface skin temperatures;
- Optical cameras and/or radiation/spectrometer instrumentation to measure canopy phenology;
- If a taller vegetation site, vertical radiation profiling;
- If a forested site, measurements of tree sap flow on the dominant tree species;
- Enhanced spatial sampling of soil temperature, moisture, and heat flux measurements.

3.3.2 Second-Generation C-Band Scanning ARM Precipitation Radar (CSAPR2)

Detailed sampling from ARM scanning cloud/precipitation radar are key components to the SE U.S. convective cloud research plan and high-priority instruments for this AMF3-BNF deployment. Ideally, the AMF3 main site would be located within 30-50 km of a second-generation C-band Scanning ARM Precipitation Radar (CSAPR2) for detailed convective cloud studies (typically, within 60 km) and surveillance to 150 km. Preferably, the CSAPR2 radar should not be located at the M1 site, e.g., typically a minimum distance >15 km allows range-height indicator (RHI) profiling over the AMF3 site while mitigating ground clutter contamination. Additional priority should be to coordinate CSAPR2 placement within 30-50 km of partner radars that may include NEXRAD and/or university options (fixed, or mobile). Select overlapping radar coverages will enable dual-Doppler convective dynamics/vertical air velocity retrievals beneficial for deep convective studies and provide redundancy in the event of an ARM radar outage. Because there is significant low-level blockage/terrain in the N. AL region, any ability to site the radar in an open field (typically, requesting 0.3-0.5 km clearance in the important sampling directions to ensure grazing angle coverage) or elevated locations (including tower or other options) should be explored.

3.3.3 X-Band and Ka-Band Scanning ARM Cloud Radar (X/Ka-SACR)

A Scanning ARM Cloud Radar (SACR) or equivalent flexible cloud/precipitation hybrid radar is also requested, with preference for the X-Ka wavelength optioned SACR. The team and ARM infrastructure partners hosted a telecon in February 2023 to discuss the potential deployment of the SACR in the second phase of the AMF3-BNF campaign, and there was universal support for an additional ARM radar to bolster the AMF3 and address a variety of anticipated regional cloud drivers. One proposed configuration for this SACR deployment is to position the radar close to the AMF3 main site (i.e., intermediary locations near Moulton, Alabama) to support detailed shallow-cloud to precipitating-cloud sampling, which cannot be as well-observed by longer-wavelength precipitation radars (e.g., CSAPR2). In expecting relatively low SE U.S. cloud bases, the usefulness of the KaSACR for shallow cloud purposes (in particular, those having cloud bases near 0.5 km and cloud tops below 4 km) at a minimum requires placement within 15-20 km (Ka-wavelengths) of the main site for effective shallow cloud sampling over the site. Given practical sampling restrictions and blockage concerns for forested deployments, a main M1 site collocation option is not the preferred choice for shallow cloud coverage/fraction (the site already will host the KAZR for vertically pointing coverage): thus, the radar would need to be offset outside of the BNF to a suitable distance for added spatial coverage. This location may also allow supplemental shallow-to-deep and deeper convective coverage from the XSACR component to this radar, which was an important science driver for the community.

A second potential configuration is one that prioritizes the Ka-X SACR (or other precipitation radar) for additional, detailed updraft/core property studies in precipitating cumulus to deeper convective conditions. These efforts would replicate SACR activities performed during AMF-Cloud, Aerosol, and Complex Terrain Interactions (CACTI), AMF-Tracking Aerosol Convection Interactions Experiment (TRACER) or similar SGP/X-band IOP periods, wherein the SACR or equivalent is operated synergistically (possibly collocated) with the CSAPR (i.e., within 30 km of each other) and multi-Doppler velocity retrieval needs. This option may alleviate siting requirements, as useful X-band ranges are an improvement (~30-40 km) for relatively unobstructed locations.

3.4 Value-Added Product Requests and Anticipated PI/Community Products

3.4.1 Value-Added Product (VAP) Requests and Data Accessibility

The baseline/core VAPs identified by the ARM Translator Plan are anticipated for this campaign, with availability according to a reasonable adaption of their scheduled timelines for a typical AMF deployment to the multi-year AMF3. In addition, the science goals for this project may benefit from continued development and improvement of ARM's related data/product services, including radar and similar plotting toolkits, ARM Data Center (ADC) and its Data Discovery, Data Workbench, Campaign Dashboard, and/or other aspects related to data product/VAP usefulness and accessibility including themes specified by ARM's recent Decadal Vision" document. Accordingly, VAP concepts of interest to the Site Science Team and wider ARM climate community for this deployment may include:

- Dual- or multi-Doppler 3D wind retrieval capability, from suitable scanning radar;
- Cloud type or echo classifications, include hydrometeor (type) from multiple sensors, radar;
- Larger-scale, synoptic regime, or similar environmental classification products towards "Virtual IOP", other Data Discovery "Epoch" search capabilities for AMF3 science drivers;
- Curated Campaign Dashboards, or similar real-time displays for PIs or Science Team members to monitor site/instrument status in nominal modes and during IOPs;
- Jupyter notebooks for easier VAP or instrument visualization (e.g., Figure 10);
- Expanded aerosol products: OACOMP, merged size distribution, kappa-products;
- Model forcing data sets using AMF3 meteorological measurements for multi-scale modeling efforts (LES, land surface modeling [LSM], atmosphere modeling);
- Team or similar modeling activities performed on ARM's ADC computing.

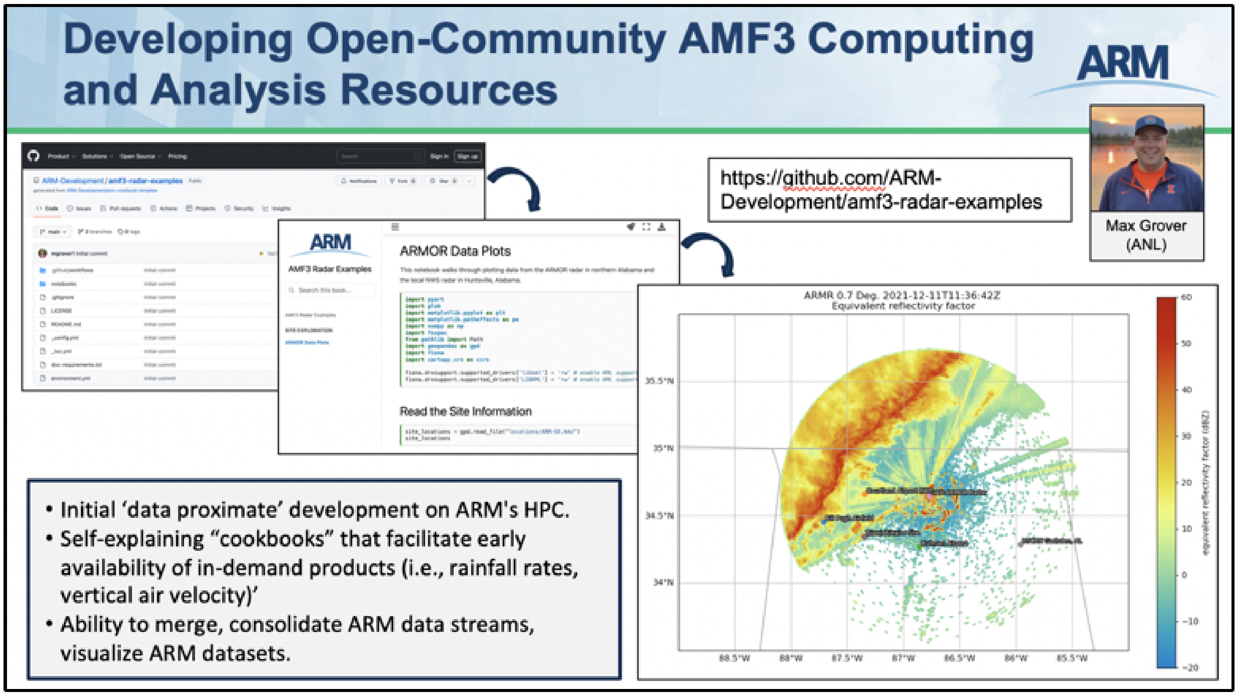

Figure 10. Example slide from the 2022 ASR/ARM PI Meeting AMF3 breakout session on pre-deployment AMF3 radar/code activities spearheaded by the Science Team and ARM developers.

3.4.2 Potential Requested Site Science Team-Led or Community-Led PI Products

In addition to requests in Section 3.4.1 that may fall within the immediate purview of ARM, its infrastructure, and translators working with PIs, our Science Team anticipates a relatively unbounded set of campaign-curated or cross-disciplinary requests originating from our team, funded ASR PIs, and/or the extended ARM climate community over any multi-year deployment. Some examples of these sorts of anticipated, community-driven products and/or needs may include some of the following:

- Advanced radar or multi-sensor "tracking", hydrometeor retrieval products, air velocity retrievals;
- Merged aerosol size distribution using SMPS, optical particle counter (OPC), and aerodynamic particle sizer (APS) measurements;
- Aerosol growth factors derived from the HTDMA;
- "Analysis-ready" and partitioned ecosystem carbon, water, and energy flux products with flux uncertainty characterization.

3.5 Collaborative SE U.S. Opportunities and Partnerships

The AMF3-BNF is expected to spark collaborations with regional partners, use existing operational observation networks, and capitalize on emerging measurement resources to accomplish science goals for this multi-year campaign. Existing resources and/or partner facility collocation therein may lessen the expected ARM infrastructure load for siting and/or ASR or Site Science Team requirements to achieve our science drivers, with emphasis on achieving spatially distributed observations. Regional partners may also provide important local synergy, support for meetings/workshops, and/or facilitate multi-agency supersite capabilities in numerous capacities for our extended deployment.

The Site Science Team has had preliminary conversations with several local partners that ARM/ASR may consider as options for longer-term efforts or as partners for IOPs centered on the N. AL region. A strength of the previous AMF3 deployment to Oliktok Point, Alaska and their associated team was a commitment to emerging technologies and pushing ARM observations forward with targeted IOP efforts (i.e., see ARM's Profiling at Oliktok Point to Enhance Year of Polar Prediction [YOPP] Experiments [POPEYE] and similar examples). Select IOP opportunities may include supporting requests for advanced aerial (e.g., TBS, UAS) or mobile ground facilities (e.g., aerosol sensor node network) that may draw from the AAF, partnerships for mobile radar/thermodynamic/aerosol profiling capabilities, or expanded tower-based facilities and similar observations (i.e., NEON mobile). These platforms, deployed for short-term projects, may expand traditional ARM cloud/aerosol coverage and heterogeneity, as well as expanded land-surface themes and inclusion of endmember land types in the SE U.S. that are not currently captured by supplemental sites (e.g., young plantation, analog site, or agriculture/grassland).

3.5.1 List of Select Regional Universities, Agencies, and Networks

- Universities in the Alabama-BNF region:
  - Alabama A&M and The Alabama Mesonet
  - Auburn University
  - University of Alabama, Huntsville (UAH)
  - University of Alabama, Tuscaloosa (UAT).
- USDA Forest Service/Forest Inventory and Analysis (FIA)
- NOAA National Weather Service (NWS) Offices (Birmingham, Huntsville, Nashville)
- Partners just outside the immediately targeted N. AL-BNF region:
  - The Paint Rock Forest Research Center, Paint Rock, Alabama
  - The Jones Center at Ichauway, Georgia
  - The Ordway-Swisher Biological Station, Florida.
- NSF National Ecological Observatory Network NEON/TALL and AmeriFlux
- NEON and NEON Mobile
- NOAA-NWS NEXRAD Network (i.e., KHTX, KGWX, KBMX)
- Northern Alabama Lightning Mapping Array (LMA, NALMA – NASA/New Mexico Tech/Georgia Tech)
- Interagency Monitoring of Protected Visual Environments (IMPROVE)
- The Environmental Protection Agency (EPA)'s Chemical Speciation Network (CSN)
- The Atmospheric Science and Chemistry mEasurement NeTwork (ASCENT)
- NASA Marshall Space Flight Center/ Global Precipitation Measurement-Ground Validation (GPM-GV) precipitation facilities

- NSF/NOAA field campaign partners previously in this region, including the VORTEX Southeast (VORTEX-SE)/Propagation, Evolution, and Rotation in Linear Storms (PERiLS).

3.5.2 Potential Internal and External IOP Concepts or Partnerships

We envision that any multi-year ARM deployment and its scientific priorities will evolve, including changes or opportunities associated with emerging capabilities or partnerships that arise during the campaign. As highlighted, the previous ARM AMF3-Oliktok Point Site Science Team (PI: Gijs de Boer) set high expectations for future AMF3 teams to actively solicit and embrace new opportunities, IOPs, and other activities of community interest. Similarly, this AMF3 BNF will provide numerous opportunities for partnerships – both internal and external to DOE and its ARM/ASR facilities and programs – through its nominal site operations as well as times (seasonally, episodically) motivated or augmented by IOPs, guest instrument deployments, and/or other collaborations or modifications that we anticipate will form around various scales in response to AMF3-BNF's cross-cutting science themes. Thus, a continuing expectation for this Site Science Team is to help promote to the ARM climate community all such possibilities for campaign efforts, which may include (but not be limited by) offering collective team guidance or knowledge of this AMF3-BNF site, its justification for its recommended instruments and operations, or support on other ARM infrastructure resources or mechanisms (e.g., Campaign Dashboards, "Epoch"-driven Data Discovery) for complementary campaigns or potential site changes.

This Site Science Team stresses that everyone in the wider ARM climate community is welcome to propose field campaigns and/or requests that range from larger/more complex resource efforts (i.e., ARM's AAF, multi-agency proposals), to temporary-to-more-permanent instrument operations/mode changes, or to smaller guest instrument deployments. Each request will be evaluated by the ARM infrastructure in separate ways and on separate time scales contingent on the request. For more information, we encourage this community to reach out to our Site Science Team; however, additional guidance on small campaign requests, guest instrument deployment, and/or select TBS activities can be found at: https://www.arm.gov/research/campaigns. Below, the Site Science Team has also compiled a listing of potential IOP and similar guest activities that this team believes can be accommodated by the AMF3-BNF, as potentially championed by this team or other members of our ARM community (with or without coordination from this team).

ARM Aerial Facility (AAF)

We anticipate the availability of AAF measurement platforms (e.g., TBS, UAS, Challenger) for IOP deployments in operational "Phase 2" (~1 year after initial site operations) in FY2025 (and following years upon request) that will target the controls of land surface heterogeneity on biosphere-atmosphere aerosol turbulent exchange, boundary-layer aerosol evolution, convective initiation, and shallow-to-deep convective transitions. For TBS deployments, we anticipate requests for seasonal deployments consisting of at least one-week periods of intensive flights with coordinated ARM and guest instrumentation capturing vertical profiles of aerosol and meteorological properties in the lower ABL. For example, we envision TBS flights during March/April, June/July, September/October, and December/January to observe the seasonal properties over the AMF3-BNF during key forest phenological periods and changes in ambient conditions.

NSF NEON Airborne Observation Platform

The Site Science Team has held conversations about including the M1 and Supplemental AMF3 sites within the NEON Airborne Observation Platform (AOP) annual flight campaigns that already cover the NEON TALL tower location. The AOP data sets would serve as important surface observations for land-surface and boundary-layer modeling (e.g., Kamoske et al. 2021). Moreover, the team suggests that ARM may consider investing in installation of select ARM instrumentation at the NEON TALL site. For a smaller investment, ARM/AMF3 would benefit from an additional LAI site in a pine-dominated landscape (using the NEON TALL eddy covariance data), but NEON and ARM would benefit from the enhanced site provided by coupling ARM boundary-layer and radiation measurements.

NASA Opportunities

Select additional NASA IOP partners from team discussions may include, but are not limited to: NASA Suborbital and Satellite Validation Studies, NASA GPM-GV, NASA Arctic Radiation-Cloud-Aerosol-Surface-Interaction Experiment (ARCSIX), Langley/Langley Research Center (LaRC), NASA Airborne Visible/Infrared Imaging (AVIRIS) and Earth Sensor Validation, NASA Atmosphere Observing System (AOS), NASA Earth Surface Mineral Dust Source Investigation (EMIT) mission, NASA Surface Biology and Geology (SBG) validation, and the NASA Tropospheric Emissions: Monitoring Pollution (TEMPO) mission.

Global Energy and Water Exchanges (GEWEX) Program

The Site Science Team has had conversations and participated in workshops and discussions around the potential role the AMF3 deployment can play in larger international efforts focused on improving our understanding and modeling of Earth's water and energy cycles. This includes discussions with the international GEWEX community, as well as participation in discussions with members of the Global Land-Atmosphere System Studies (GLASS) panel regarding the potential of the AMF3 deployment in evaluating and improving the modeling of multi-scale land-atmosphere coupling (LoCo) processes. This also includes participation in international workshops focused on identifying model needs and observational requirements for sites to inform LoCo studies.

Potential Aerosol Process Studies IOPs

- *Biomass Burning IOP:* Prescribed fires are frequently employed in this region to eliminate excess agricultural byproducts after crop harvesting, especially in regions growing corn, soybean, wheat, and rice. Agricultural burning exhibits strong seasonal tendencies, with a small peak in emissions in June, and a large fire season from September to November. The AMF3 deployment will provide key measurements of surface-observed BB aerosol microphysical, chemical, and optical properties, which will be coupled with selected optical property measurements using an ARM TBS deployment of optical extinction and absorption (advanced instrumentation). TBS impactors will be requested for collection of particle size cuts for offline compositional analysis. The microphysical properties of BB aerosols such as the size distribution will be obtained with a merged aerosol size distribution as discussed above. Chemical properties of BB aerosol will be obtained using the ACSM and OACOMP, which together will estimate different types of organic aerosol, including BB organic aerosol.

- *AOS Closure IOP:* Shakedown effort for the AOS to evaluate multi-instrument/measurement closure to improve our understanding of aerosol data quality. Activities will include characterization and comparisons of aerosol hygroscopicity derived from a higher-order synthesis of sub-saturated water uptake (e.g., HTDMA, AMBIENT/WET NEPH), super-saturated water uptake (e.g., CCN), aerosol chemical composition (e.g., ACSM, SP2-XR), and aerosol microphysical properties (e.g., SMPS, CPC). Other multi-measurement closures can include optical, chemical composition, and size distribution.
- *NPF IOP:* Explore the relative roles of isoprene and monoterpene oxidation chemistry in suppressing/enhancing NPF targeting specific regimes (e.g., growing season).
- *Bioaerosol IOP:* Explore the potential emissions of bioaerosols from the site. For pollen, IOP would be timed with spring tree emissions (March-May), with the standard AOS package plus WIBS. Seasonal TBS deployments could address the vertical structure of bioaerosol.
- *BVOC and Stress IOP:* If specific conditions occur (e.g., seasonal drought forecasts, extreme heat), IOPs could be recommended to investigate the role of drought or heat waves on stress-induced BVOC emissions. This would require additional gas-phase chemistry monitoring of speciated monoterpenes and would allow links to SOA formation.

Potential Convective Cloud Studies IOPs

- *Yearly Deep Convective-Scanning Radar IOPs:* Initially, these may include shakedown/kick-off efforts for the ARM CSAPR2 radar to evaluate radar operations, data quality (engineering design/conditioning), products, and coordinated scanning with local partner radar (tentatively, summer 2024). These activities may also be expanded to include coordinated forecasting efforts (with yearly team support, ARM mentors and translators, PI, and local university partners) on a yearly basis to identify appropriate events for operation, and evaluation of data sets in real time, like previous ARM campaigns (i.e., Mid-latitude Continental Convective Clouds Experiment [MC3E], CACTI, TRACER). The Site Science Team envisions coordinating these efforts, with additional flexibility around particular seasons of interest, i.e., contingent on the reception of initial kick-off activities.
- *Agile or Advanced Radar Scanning IOPs:* Following the success of the previous ARM TRACER campaign and similar episodic operations at SGP, the Science Team anticipates future community demand for IOPs that speak to creative radar modes and operations. Dates and duration will be contingent on data collection needs (i.e., if/when SACR is available for this purpose), possibly targeting shallow-to-deep transitions in the summertime, or isolated deep convection in the spring to summer, as also following PI/community support and ARM Engineering availability. It is not anticipated that agile or forms of less aggressive mode-change radar operations (i.e., daily or sub-daily mode changes) would be possible prior to FY25. The Site Science Team anticipates a minimum of a year of CSAPR2/SACR operations from the ARM radars prior to aggressive modifications of nominal/relatively fixed scanning modes (set volume coverage patterns [VCPs], etc.) to agile designs. However, how the radars are operated under various seasons or regimes to achieve science goals should be a continuing point of community discussion.
- *Thermodynamic Profiling and Distributed Sensor Network IOPs:* The Science Team anticipates multiple activities to target an improved understanding of the regional spatiotemporal variability of thermodynamic profiles, the associated cloud fields, and the role of ARM observations therein. Initial IOP activities may support enhanced radiosonde launch frequency at the main site, or additional

radiosondes launched at supplemental sites (i.e., those within 30-50 km of the main location). Changes in sounding operations may change contingent on forecast cloud conditions, as in previous ARM campaigns (i.e., MC3E, CACTI, TRACER). Similarly, the team anticipates potential partnerships with distributed cloud and thermodynamic profiling facilities, including several mobile/deployable options in the region. This IOP request could include ARM launching 8/day radiosondes at BWWC for a set number of events during a specific regime or season (as compared to the nominal 4/day schedule) per year, most likely targeting the spring or summer months when deeper convection or shallow-to-deep transitions are prevalent. However, this request could also consider launching 4/day radiosondes (or similar) at a supplemental site (i.e., Courtland airport, or other ARM supplemental/partner sites) to explore spatial variability in thermodynamic profiling. From recent ARM campaign examples (i.e., TRACER), typical requests are often for as many as 20 enhanced sounding days per IOP (approximately, 100 additional radiosondes per IOP). The Site Science Team recommends that ARM consider earmarking a similar quantity of additional radiosondes for yearly IOPs, starting as early as spring 2024 (in conjunction with radar IOPs) or 2025.

- *Cloud-Type or Retrieval-Driven IOPs:* Regional partners have expressed interest in IOPs for the focused study of summertime shallow-to-deep convection, QLCS, and potential site operation changes that support retrievals for key quantities of interest (i.e., vertical air velocity in deep convective clouds). These may benefit from partner assets including mobile profiling, radar, and other emerging technology.

Potential Land-Surface Interaction/Cross-Coupling IOPs

- *Tree Sap Flux and Ecosystem Water Cycling:* A guest deployment of an automated tree sap flow system could characterize the variability in plant transpiration and contribution of different tree species to surface moisture and energy fluxes. This would help partition the transpiration component of latent heat flux and improve scaling from trees to the ecosystem scale measured with the eddy covariance approach. Additional constraint on the partitioning of evaporation and transpiration using flux tower observations could come from short-term guest instrumentation (e.g., Picaro LI-2130i) installed vertically on the AMF3-BNF tower measuring water isotope mixing ratios. When paired with measurements of carbon isotope ratios (Fiorella et al. 2021) of within- and above-canopy carbon dioxide measured by the PGSISO, water isotope ratio measurements can help resolve the coupled water and carbon cycles and their response to environmental variability and change, as well as providing a more meaningful measurement of the energy and moisture controls on boundary-layer evolution. A similar configuration can be found on existing NEON towers (Finkenbiner et al. 2022).
- *Canopy Physiological Processes:* The Site Science Team anticipates a strong need to characterize the photosynthetic capacity of the AMF3-BNF canopy during peak seasonal greenness (e.g., July), spring, fall, and winter. An intensive canopy processes field campaign would be designed to quantify the leaf-level and vertical distribution of photosynthetic capacity and stomatal conductance of the dominant vegetation to link with sap flux and ecosystem-scale measurements provided by the EC system, and to inform modeling. These measurements could also be paired with leaf/branch-level measurements of BVOC emissions to link seasonal gas exchange and aerosol precursor fluxes and sources.
- *Characterizing the Canopy Radiation Regime and Thermal Properties to Inform the Modeling of Canopy Radiative Transfer and Surface Temperatures:* Characterize the 3D canopy radiation and thermal environment at the AMF3-BNF M1 site. An IOP could quantify horizontal/vertical

distribution of stems, twigs, and leaves as well as the average seasonal single-scattering albedo of these properties (plant and soil surface albedo) and in-canopy light profiles. Deployment of a terrestrial lidar scanner (TLS) and/or airborne lidar with tower based on remote-sensing spectrometers could provide structure and albedo information useful for evaluating DTS measurements to test turbulence assumptions. Existing lidar for the site (Figure 9, Alabama Lidar Data Set) is from 2012 and regularly updated (annually, or every two-three years) information on canopy structure would be preferable. Using PI UAS or airborne systems (e.g., NEON AOP), regularly updated lidar and spectral information would be possible. A second short-term deployment of a guest DTS installed horizontally under the canopy would provide information on the spatial variation in under-canopy turbulence processes and contributions to overall fluxes. A similar set of IOPs focused on supplemental sites with a tower sited in a vegetation canopy would also be useful for informing models simulating the regional surface moisture and energy fluxes.

- *Seasonal Canopy Spectral Properties and Solar-Induced Fluorescence (SIF):* A guest IOP deployment of spectroradiometer systems could be used to characterize the full shortwave albedo as temporal variation in vegetation reflectivity (providing the bi-directional reflectance distribution function or BRDF). Similarly, a high-resolution spectrometer system to measure variation in SIF could provide information on seasonal canopy photosynthesis (Magney et al. 2019). Combined with albedo measurements, surface temperature (using radiometers), and vegetation phenology (from a camera network), these data would allow for linking vegetation properties to eddy covariance surface fluxes and atmospheric conditions.

- *Quantifying the Integrated Terrestrial Controls on Aerosol Sources, Transformations, and Climate Impacts:* In the forested environment of the AMF3, the terrestrial controls on PBAP emission and NPF from the photochemical reaction of BVOCs are expected to play critical roles as aerosol sources in the ABL. However, these processes are poorly understood due to uncertainties in the underlying aerosol microphysical mechanisms and the ABL dynamical controls on the vertical distribution of PBAPs and BVOCs. The latter includes limited understanding of how the seasonality in vegetation function and fluxes drives temporal variation in emission rates and migration into the upper atmosphere, which further obscure characterization of terrestrial aerosol controls due to the simultaneous mixing and aerosol processing during vertical transport. This potential IOP aims to quantify the terrestrial controls on aerosol sources within the ABL at AMF3-BNF by characterizing the atmospheric vertical distribution of PBAPs, BVOCs, and the resulting NPF in the ABL above the forested environment, and by connecting these profiles to measured seasonal surface-atmosphere fluxes to link forest functioning with aerosol dynamics. These vertically resolved measurements will be combined with planned surface- and tower-based aerosol and atmospheric state observations, integrated into high-resolution land-atmosphere models, to develop a more complete understanding of the contribution of vegetation dynamics and soils to the terrestrial controls on atmospheric aerosol.

4.0 Emerging Technologies and Opportunities

The Site Science Team envisions the AMF3-BNF must be flexible to incorporate or accommodate emerging technologies that allow ARM and ASR to accomplish their scientific mission(s) through this AMF3 deployment. As with IOPs and similar campaign requests, our Site Science Team will encourage these activities from the various scientific communities that can benefit from the deployment. Several potential concepts that expand the scientific reach of the site could include:

- **Mobile measurement platforms for biological aerosol**: For example, emerging AAF TBS, UAS, and/or Challenger aircraft opportunities.
- **Seasonal carbonyl sulfide fluxes** to improve the partitioning of ecosystem respiration.
- **Water isotopic mixing ratio measurements to improve T/evapotranspiration (ET) partitioning.**
- **Paired branch-level measurements of photosynthesis and BVOC emission rates under different environmental conditions connected with tower-based aerosol flux observations.**
- **Additional access to modeling activities on ARM's ADC high-performance computing (HPC; i.e., Cumulus).**
- **Artificial intelligence (AI)/machine learning (ML) approaches for automated data QA/QC, data synthesis, and process model emulation.**
- **Near-surface remote sensing and surface-atmosphere coupled UAS profiling**: Should include within-day and seasonal measurements of canopy albedo and surface temperatures, and preferably combined with above-canopy aerosol measurements. Annual high-resolution canopy lidar profiling from UAS platforms. This would provide important information on the spatiotemporal variation in surface energy exchange and vegetation-aerosol coupling.
- **Multi-site deployment of a fixed or portable DTS for AMF3 LAI and BL science.**
- **Atmospheric profiling of total column CO_2 and water vapor**: Deployment of a Total Carbon Column Observing Network (TCCON) system for vertical characterization of gas concentrations and for satellite validation.
- **ARM LASSO AMF3-BNF**: We anticipate that the development of new Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) scenario(s) for the AMF3-BNF campaign could be of great benefit to advancing multiple science drivers and connections for these site observations to the climate modeling community. The team expects multiple pathways for participating in planned workshops to discuss how various scenarios could be configured across several of our cross-cutting aerosol-cloud-LAI themes.
- **AmeriFlux Rapid Response (ARR) and NEON MDP deployments**: Targeting additional surface endmembers in key ecosystems and landcover types. Could include high-priority land cover types not currently captured with AMF3, target working forest fluxes.

5.0 Site Science Team Community Outreach and Acknowledgments

In this section, the Site Science Team provides a curated list of team outreach and solicited community feedback that contributed to the development of this Science Plan its recommendations. This list includes select invited presentations and town hall engagements to audiences in DOE, ASR/ARM, and the wider climate community.

5.1 Select List of Site Science Team-Solicited Community Feedback

5.1.1 ASR/ARM Constituent Groups and AMF3 Partners

- AMF3 OLI Site Science Team
- ARM-ASR Coordination Team (AACT)
  - ASR's Aerosol Processes Working Group
  - ASR's Convective Clouds Working Group
  - ASR's Warm BL Process Working Group
- ARM's Aerosol Measurement Steering Group (AMSG)
- ARM's Cloud and Precipitation Measurement Steering Group (CPMSG)
- ARM's translators
- ARM's User Executive Committee (UEC).

5.1.2 Internal DOE Laboratory and User Facility Outreach

- ANL: ARM and AMF instrumentation/infrastructure
- LANL: TCCON
- LLNL: LAI-convection science
- LBNL: ARM stereo camera mentors
- PNNL: ARM radar engineering mentors
- PNNL: Integrated Cloud, Land-surface, and Aerosol System Study (ICLASS) Science Focus Area (SFA)
- BNL-ANL: Process-Level Advancements of Climate through Cloud and Aerosol Life Cycle Studies (PASCCALS) Science Focus Area (SFA)
- DOE Environmental Molecular Sciences Laboratory (EMSL)
- DOE Environmental System Science (ESS).

5.1.3 Key External Stakeholder Outreach

- The EPA's Chemical Speciation Network (CSN)
- The Atmospheric Science and Chemistry mEasurement NeTwork (ASCENT)
- Alabama Cooperative Extension System (ACES)
- Aerosol, Cloud, Precipitation, and Climate Working Group (ACPC)
- AmeriFlux
- Global Energy and Water Exchanges (GEWEX)/Global Land-Atmosphere System Studies (GLASS)
- Interagency Monitoring of Protected Visual Environments (IMPROVE)
- NASA/NOAA Satellite Sounder Retrieval Community
- NASA Marshall, NASA's GPM-GV
- NASA EMIT, NASA AOS
- National Ecological Observatory Network (NEON) Operations and Science Team
- Northern Alabama Lightning Mapping Array (NALMA).

5.1.4 Additional SE U.S. Regional and University Outreach

- The University of Alabama – Huntsville
- The University of Alabama – Tuscaloosa
- Alabama A&M University
- Auburn University
- NSF/NOAA Vortex-SE/PERiLS
- The U.S. Forest Service/FIA
- Bankhead National Forest
- Talladega National Forest
- Southern Oxidant & Aerosol Study (SOAS) leadership.

5.2 Sampling of Site Science Team Community Workshop, Town Hall, and/or Invited Presentations

- Town hall, AGU Fall Meeting 2020. "Science and Deployment Plan for the DOE Third Atmospheric Radiation Measurement Mobile Facility: Coupled Observational–Modeling Studies of Land–Aerosol–Cloud Interactions in the Southeastern United States."
- Breakout session, 2020 ASR/ARM PI Meeting. "Deployment of the Third ARM Mobile Facility to the Southeastern United States."
- Invited talk, 2020 ESS PI Meeting. "ARM Mobile Facility Deployments: SAIL and Southeastern United States."
- Invited talk, 2020, ACPC Working Group. "The Third ARM Mobile Facility: Coupled Observational-Modeling Studies of Land-Aerosol-Cloud Interactions in the Southeastern United States," C Kuang.
- Town hall, 2021 AMS Annual Meeting. "Science and Deployment Plan for the DOE Third Atmospheric Radiation Measurement Mobile Facility: Coupled Observational-Modeling Studies of Land-Aerosol-Cloud Interactions in the Southeastern United States."
- Invited talk, 2021 University of Alabama – Huntsville. "Boundary-Layer New Particle Formation: Instrument Development, Field Measurements, and Future Deployments," C Kuang.
- Invited talk, 2022 EMSL LAI workshop.
- Invited talk, 2022 ASR Future of LES workshop, S Serbin.
- Breakout session, 2022 ASR/ARM PI Meeting. "Deployment of the Third ARM Mobile Facility to the Southeastern United States."
- Invited talk, 2023 University of Miami CAST workshop.
- AMF3 Site Science Team (SST)/ARM AMF-SACR deployment telecon, 2023, S Giangrande.
- Breakout session, 2023, ASR/ARM PI Meeting. "AMF3 BNF: Advancing a next-generation model-observing system testbed for integrative land-aerosol-cloud studies in the Southeast United States."
- Invited talk, 2023, DOE's Environmental System Science Southeast Land-Atmosphere Research Opportunities Workshop (SELARO), S. Serbin.

6.0 Project and Site Management

The AMF3 will primarily operate in nominal modes, as defined by ARM instrument mentors and the AMF3 operations team. For initial operations, the Science Team will provide guidance for baseline collections and strategies as outlined in the previous sections. As campaign operations mature, we anticipate that ARM and the AMF3 operations team will operate sites like fixed-site operations when not otherwise in requested IOP operational modes (episodic).

6.1 Data Management Plan

The climate research data publicly funded by DOE's Office of Biological and Environmental Research (BER) are a public trust and shall be freely available. These data should be preserved, documented, quality-assured, and discoverable by any who request it. The following sections document the process by which data/metadata resulting from these site operations will adhere to those basic requirements.

6.1.1 Data Sharing and Preservation

Data sets generated from ARM instruments collected during this deployment will be quality-controlled and delivered to the ARM Data Center (www.arm.gov/data) and its archive by the ARM instrument mentors. In addition, eddy covariance data sets collected using AmeriFlux instrumentation will also be delivered and archived through the AmeriFlux data portal. The Site Science Team will aid in the evaluation of the data quality through regular visualization and evaluation of datastreams during the campaign and through interaction with the AMF operations team. This may include regular interactions with ARM's campaign browsers or other display tools, the use of an ARM Field Campaign Dashboard, and development of automated data evaluation codes. Any data quality issues identified by the Site Science Team will be communicated to ARM through the AMF operations team, the ARM instrument mentors, and through the Data Quality Problem Reporting (DQPR) system.

Higher-order data products and code will be produced by PIs, the Site Science Team, and ARM and ASR, potentially under separately funded research grants. Products originating from the Science Team (and its partners) will be submitted as PI Products to the ARM ADC using the ARM Product Registration and Submission Tool. Higher-order flux data products will also be archived on the AmeriFlux data portal. Code resulting from the Site Science Team will be also made available via appropriate online repositories including ARM/Github or ARM/ASR-preferred options. The team also anticipates collaborating with ARM's mentors, translators, and developers to produce campaign-specific products for release by ARM, and associated code housed by ARM's code repository. Data sets and model outputs collected by collaborative resources (i.e., NEXRAD) may also be archived, subject to availability from those groups, agencies, and/or data sharing agreements with ARM. With the assistance of ARM's ADC staff, all data products generated by our team will be assigned Digital Object Identifiers (DOIs) to facilitate citation and visibility. Research results and the data sets from these efforts will be published and cited in peer-reviewed scientific papers. Preliminary results will be presented at conferences as posters and/or oral presentations. All research data displayed in publications resulting from the proposed activities will be digitally accessible shortly after the manuscript is accepted for publication via its DOI. This includes all data required to validate/reproduce published results.

6.1.2 Data Types, Sources, Content, and Format

The proposed campaign will generate several different types of data including direct measurements from ARM instruments, higher-order retrievals and products, and output from atmospheric model simulations at different scales. These data types will often exist in both raw and processed forms with associated metadata. All data files from the campaign will be preserved and shared in appropriate standard data formats for ARM (e.g., NetCDF, ASCII). Relevant descriptive metadata will be included and at a minimum contain the date/time of collection or processing, location (latitude, longitude) and description (e.g., instrument status), PI contact information, data provenance, primary measurements, and stratum keywords using community standards.

6.2 AMF3 Site Science Team Expected Code of Conduct

The AMF3-BNF Site Science Team recommends that interested ARM/ASR staff, PIs, or similar agency/university/laboratory researchers, guests, and/or external contractors/visitors for this AMF3 deployment consider carefully reviewing and bookmarking the following Code of Conduct expectations outlined by ARM. Consistent with the policies and procedures provided within this Code of Conduct, the Site Science Team would encourage that if, during these AMF3-BNF campaign efforts, users experience, witness, or have knowledge of behavior contrary to these expectations, they report the incident by contacting an ARM-designated point of contact, as well as reach out to Site Science Team members. As a team, we expect that everyone associated with this deployment treat each other with respect and consideration.

7.0 Relevance to DOE

The Biological and Environmental Research Advisory Committee's Grand Challenges report (BERAC 2017) included several action items within the Earth and Environmental Sciences subtopic to which the deployment of the AMF3 to the SE U.S. in the Bankhead National Forest and the accompanying science plan are directly relevant. These action items include: (1) To advance high-resolution modeling in different simulation and prediction modes supported by exascale computing to improve understanding and prediction of extreme or high-impact events, (2) To develop and integrate new sensing technologies and optimize field deployments in ARM to explore interactions across different scales of biological organization and biosphere-atmosphere feedbacks, and (3) Create new integrated field laboratories that target biogeochemical, energy, and water flows between urban areas and surrounding ecosystems. The focus of the proposed AMF3-BNF science plan that stresses the interrelationships among continental convection, fluxes from dense vegetative land cover, and aerosol sources that drive weather and climate patterns falls squarely within each of these action items.

The DOE ARM mission emphasizes providing "the climate research community with strategically located in situ and remote-sensing observatories designed to improve the understanding and representation, in climate and Earth system models, of clouds and aerosols as well as their interactions and coupling with the Earth's surface" (ARM 2014). A focus on the SE U.S., with its documented lack of regional warming compared to the continental U.S. and worldwide trends, provides an opportunity to challenge and improve our understanding of the processes that drive this anomalous behavior. The proposed research plan emphasizes understanding of the cloud, aerosol and land characteristics in this region, and the processes that drive their life cycle and interactions.

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