U.S. DEPARTMENT OF ENERGY | Office of Science

DOE/SC-ARM-24-016

Coastal-Urban-Rural Atmospheric Gradient Experiment (CoURAGE) Science Plan

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How to cite this document:

Davis, K, B Zaitchik, A Asa-Awuku, E Bou-Zeid, S Baidar, C Boxe, WA Brewer, S Chiao, R Damoah, P DeCarlo, B Demoz, R Dickerson, M Giometto, J Gonzalez-Cruz, M Jensen, C Kuang, K Lamer, X Li, K Lombardo, N Miles, D Niyogi, Y Pan, J Peters, P Ramamurthy, W Peng, S Richardson, R Sakai, D Waugh, and J Zhang. Coastal-Urban-Rural Atmospheric Gradient Experiment (CoURAGE) Science Plan. 2024. U.S. Department of Energy, Atmospheric Radiation Measurement user facility, Richland, Washington. DOE/SC-ARM-24-016.

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

Abstract

Understanding the mechanisms governing the urban atmospheric environment is critical for informing urban populations regarding the impacts of climate change and associated mitigation and adaptation measures. Earth system (climate and weather) models have not yet been adapted to provide accurate predictions of climate and weather variability within cities, nor do they provide well-tested representations of the impacts of urban systems on the atmospheric environment. These limitations are largely due to limited field data available for testing and development of these models.

We will deploy the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility's first Mobile Facility (AMF1) to the mid-Atlantic region surrounding the city of Baltimore for the Coast-Urban-Rural Atmospheric Gradient Experiment (CoURAGE). This deployment will create a four-node regional atmospheric observatory network including Baltimore and its three primary surrounding environments – rural, urban, and bay.

CoURAGE investigators will study the interactions among the Earth's surface, the atmospheric boundary layer, aerosols and atmospheric composition, clouds, radiation, and precipitation at each site, and examine how the spatial gradients across the region interact to create the climate conditions in Baltimore.

This study will determine the degree to which Baltimore's atmospheric environment depends on interactive feedbacks in the atmospheric system and the degree to which conditions in Baltimore depend on the surrounding environment. Some topics of interest include how urban land management exacerbates heat waves, the impact of regional mesoscale winds (nocturnal jet, bay breeze) on urban air pollution and cloud cover, and the impact of the urban heat island and aerosol production on heavy precipitation events. *Understanding this integrated coast-urban-rural system quantitatively and with good accuracy and precision is critical to informing climate adaptation and mitigation efforts in the city of Baltimore*. The understanding gained should be applicable to many similar coastal, mid-latitude urban centers.

Another important objective of CoURAGE is to improve the representation of the climate of coastal cities in Earth systems models (ESMs). CoURAGE investigators will use the observations to test current ESMs, identify weaknesses and work towards improved simulations of this complex environment.

The ARM core facility will be deployed in the city of Baltimore, complementing the Baltimore Social-Environmental Collaborative (BSEC), a DOE urban integrated field laboratory (UIFL). Ancillary sites will be deployed to rural Maryland northwest of Baltimore, and to the southern end of Kent Island within Chesapeake Bay. The fourth node will be a long-term atmospheric observatory operated in Beltsville, Maryland by Howard University and the Maryland Department of the Environment. Measurements will be conducted for one year, starting in December of 2024. There will be two intensive operational periods (IOPs), one in summer and one in winter, when the ancillary sites will be enhanced with additional balloon launches, tethered balloon system (TBS) operation, and added atmospheric composition measurements.

Acronyms and Abbreviations

3D	three-dimensional
4D	four-dimensional
ABL	atmospheric boundary layer
ACMS	aerosol chemical speciation monitor
AERI	atmospheric emitted radiance interferometer
AERONET	Aerosol Robotic Network
AMF1	first ARM Mobile Facility
AMS	aerosol mass spectrometer
AOS	Aerosol Observing System
ARM	Atmospheric Radiation Measurement
ASOS	Automated Surface Observing System
ASRC	Atmospheric Sciences Research Center
BNL	Brookhaven National Laboratory (DOE)
BSEC	Baltimore Social-Environmental Collaborative
CAP	Cooperative Agency Profiler
CAPE	convective available potential energy
CCN	cloud condensation nuclei or cloud condensation nuclei particle counter
CI	convection initiation
CIN	convective inhibition
CMAQ	Community Multiscale Air Quality (CMAQ) Model
CMAS	Center for Multiscale Applied Sensing (BNL)
Co-I	co-investigator
CoURAGE	Coastal-Urban-Rural Atmospheric Gradient Experiment
CPC	condensation particle counter
CSPHOT	sunphotometer
DL	Doppler lidar
DOE	U.S. Department of Energy
DTS	distributed temperature sensor
E3SM	Energy Exascale Earth System Model
EC	eddy covariance
ELM	E3SM Land Model
EMSL	Environmental Molecular Sciences Laboratory
ESM	Earth system model
ESRL	Earth System Research Laboratory (NOAA)
FAA	Federal Aviation Administration
GCOS	Global Climate Observing System
GHG	greenhouse gas monitor

GLOBUS	Global Building Heights for Urban Studies
GNDRAD	ground radiometers on stand for upwelling radiation
GRUAN	GCOS Reference Upper-Air Network
HU	Howard University
HUBC	Howard University Beltsville Campus
HUIRB	Howard University Interdisciplinary Research Facility
IAD	Sterling, Virginia
IOP	intensive operational period
IRT	infrared thermometer
JHU	Johns Hopkins University
KAZR	Ka-band ARM Zenith Radar
LCL	lifting condensation level
LDIS	laser disdrometer
LFC	level of free convection
LLJ	low-level jet
LTAR	Long-Term Agroecosystem Research
MADIS	Meteorological Assimilation Data Ingest System (NOAA ESRL)
MDE	Maryland Department of Environment
microAeth®	tradename of a micro aethlometer manufactured by AethLabs
MPL	micropulse lidar
MSD-LIVE	MSD-LIVE: The MultiSector Dynamics – Living, Intuitive, Value-adding, Environment
mSEMS	miniaturized scanning electrical mobility particle sizer
MSU	Morgan State University
MWR	microwave radiometer
NASA	National Aeronautics and Space Administration
NEON	National Ecological Observatory Network
NetCDF	Network Common Data Form
NEXRAD	Next-Generation Weather Radar
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
Noah-MP	Noah land-surface model with multiparameterization options
NWS	National Weather Service
ORG	optical rain gauge
ORNL	Oak Ridge National Laboratory (DOE)
PI	principal investigator
POPS	portable optical particle spectrometer
PSU	The Pennsylvania State University

PU	Princeton University
RASS	radio acoustic sounding system
RWP	radar wind profiler
SACR	Scanning ARM Cloud Radar
SASHE	shortwave array spectroradiometer-hemispheric
SBF	sea breeze front
SCREAM	Simple Cloud-Resolving E3SM Atmosphere Model
SEBS	surface energy balance system
SGP	Southern Great Plains
SKYRAD	sky radiometers on stand for downwelling radiation
SLUCM	single-layer urban canopy model
SMPS	scanning mobility particle sizer
SOA	secondary organic aerosol
STAC	size- and time-resolved aerosol collector
STERCAM	stereo cameras for clouds
TBS	tethered balloon system
TDWR	terminal Doppler weather radar
TRACER	Tracking Aerosol Convection Interactions Experiment
TRMM	Tropical Rainfall Measuring Mission
TSI	total sky imager
UA	University of Albany – State University of New York
UCM	urban canopy model
UCN	Unified Ceilometer Network
UHI	urban heat island
UIFL	urban integrated field laboratory
UM	University of Maryland
UMBC	University of Maryland, Baltimore County
USDA	United States Department of Agriculture
VAP	value-added product
VDIS	video disdrometer
WAL	Wallops Island, Virginia
WBRG	weighing bucket rain gauge
WRF	Weather Research and Forecasting Model
WRF-BEP	Weather Research and Forecasting Model with Building Effect Parameterization
WRF-Chem	Weather Research and Forecasting Model coupled with Chemistry
WRF-LES	Weather Research and Forecasting Model with Large-Eddy Simulation
WUDAPT	World Urban Database and Access Portal Tool

Contents

Figures

Tables

1.0 Background

Understanding the mechanisms governing the urban atmospheric environment is critical for informing urban populations regarding the impacts of climate change and associated mitigation and adaptation measures. Earth system (climate and weather) models have not yet been adapted to provide accurate predictions of climate and weather variability within cities, nor do they provide well-tested representations of the impacts of urban systems on the atmospheric environment. These limitations are largely due to limited field data available for testing and development of these models (NRC 2012).

The need to improve the representation of cities in Earth system models (ESMs) and the performance of ESMs in urban environments is urgent. Fortunately, both our ESMs and our observational systems have developed to the point where they have the potential to contribute to significant progress in understanding the urban atmospheric environment, including interactions among the atmospheric boundary layer, atmospheric composition, cloud cover, radiation, and precipitation (Figure 1). This need for state-of-the-science atmospheric observations of the urban atmospheric environment motivates our request for the first ARM Mobile Facility (AMF1).

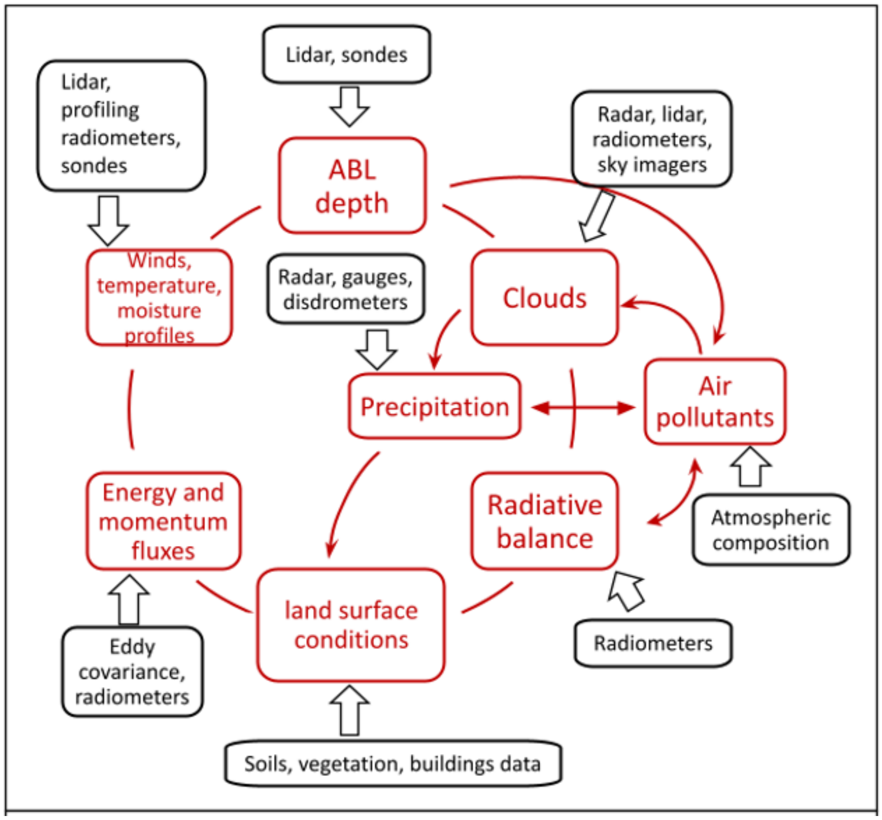


Figure 1. AMF1 and collaborator observations (black) will observe all components of the surface-atmospheric boundary layer (ABL)-cloud-atmospheric composition-radiation interactive system (red). These multi-state observations will enable a uniquely comprehensive study of how coast-urban-rural gradients in the Baltimore region interact to form the Baltimore atmospheric environment.

We propose to deploy the AMF1 to the mid-Atlantic domain surrounding the city of Baltimore (Figure 2) for the CoURAGE field campaign. Baltimore is the site of the BSEC, a DOE UIFL. Baltimore is typical of many mid-latitude, continental-climate east coast cities.

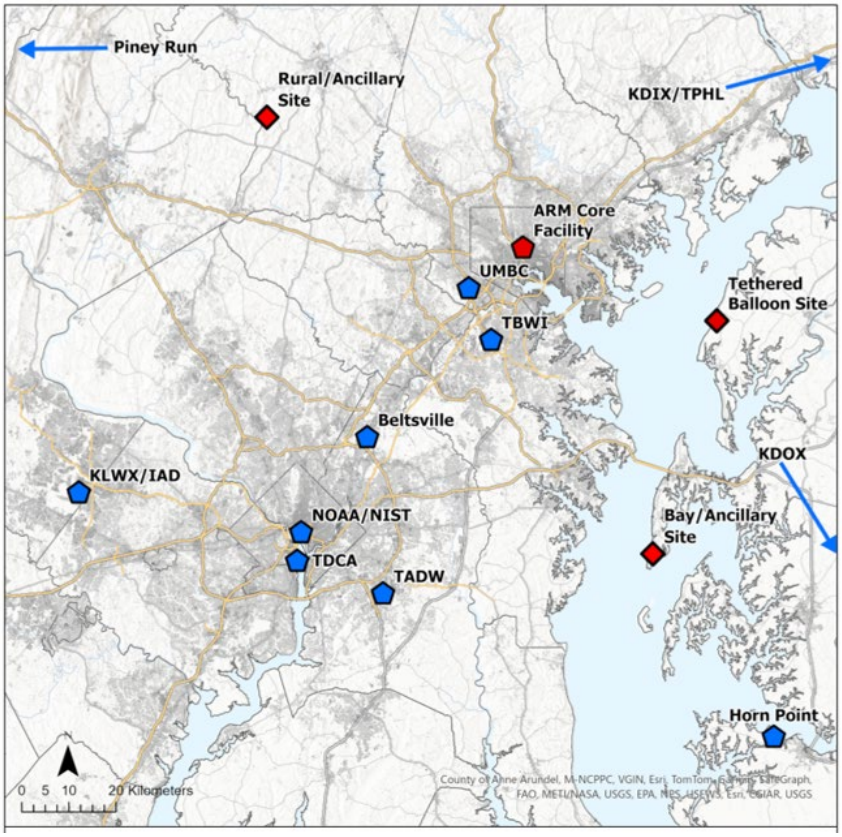


Figure 2. Study domain for CoURAGE. The AMF1 core and ancillary sites (red) would complement an existing regional network of atmospheric profiling and scanning radar stations (blue). We request a core site in the city of Baltimore, and ancillary sites in rural Maryland Kent Island in Chesapeake Bay. These would be complemented by atmospheric composition and atmospheric profiling data upwind in Beltsville (Howard University and the Maryland Department of Environment [MDE]) and Washington, D.C. (NOAA/ National Institute of Standards and Technology [NIST]), operational wind profiling (MDE) at Piney Run and Horn Point, National Weather Service (NWS) rawinsonde launches from Dulles airport (IAD), and multiple scanning Doppler weather radar (K and T prefix four-letter sites, NWS, Federal Aviation Administration [FAA], Air Force). The ARM core site in Baltimore complements the observations of the BSEC UIFL (Figure 4). Background shading shows the fraction of impervious surface.

The coastal environment has a strong impact on synoptic weather conditions. Summer Bermuda high-pressure systems lead to hot, humid, stagnant conditions and fronts that often stall and become stationary in the coastal zone, fall tropical storms remnants can bring extreme rainfall, and coastal winter storms grow in intensity due to the sea-land contrast. Folded into the dynamic synoptic setting are the modifications of the atmospheric environment caused by the micro- to meso-scale coast-urban-rural gradients. Densely vegetated rural lands, forested and agricultural, border the urban environment to the northwest. Heavily developed urban sprawl lies between this rural background and a complex coastal zone to the east.

Urban landscapes are known to modify the atmospheric environment, reducing local evapotranspiration, changing the heat capacity of the surface, contributing anthropogenic sources of heat and moisture, altering surface roughness and albedo, and altering atmospheric composition through emission of aerosols and other pollutants (Lamer et al. 2022, Zhao et al. 2020). These modifications have been shown to lead to an urban heat island (UHI), modification of the urban atmospheric boundary layer, modification of cloud properties, intensification of local convective precipitation, and degradation of local air quality through primary emissions and secondary chemical processes (e.g., ozone and aerosol formation). Both coastal-urban and urban-rural gradients may lead to mesoscale flows including bay breezes and low-level jets.

The degree to which the rural, marine, and urban systems interact to create the atmospheric environment of mid-latitude coastal cities remains highly uncertain, largely due to limited observational records, hindering our ability to disaggregate this array of environmental drivers (Grimmond et al. 2020). Further, the interactions among the elements of the urban atmospheric environment, including surface fluxes, the boundary layer, atmospheric composition, cloud cover, radiation, and precipitation, also remain uncertain (Masson et al. 2020), largely due to limited observations of the entirety of this interactive system (Figure 1). Projections of future urban climate, including the responses of the urban environment to future land management, and changes in climate, energy, and industrial systems, depend on accurate and precise representation of these interactions in ESMs. We focus on four key components of the interactive atmospheric system: ABL dynamics, atmospheric composition, clouds and radiation, and precipitation.

1.1 Urban Atmospheric Boundary Layer

Topics such as the UHI have been studied for decades (Oke 1973, Stewart 2011). We know from a plethora of past research (Barlow 2014, Oke et al. 2017) that urban systems modify land-atmosphere fluxes, ABL development, and the resulting atmospheric environment. Prior studies have been limited in two important ways. One is the lack of observations of the complete causal chain (Figure 1) that governs urban ABL development. Observations of a limited number of components of this chain makes it difficult to draw definitive conclusions about what processes lead to the unique properties of the urban ABL. Second, past studies rarely include detailed observations of the ABL dynamics surrounding the urban system, limiting our understanding of how spatial gradients and advection lead to the urban ABL (Niyogi et al. 2006, Sarmiento et al. 2017). As a result, it is difficult to evaluate the degree to which urban ABL characteristics are determined by urban land-surface processes versus influenced by upwind conditions.

Heterogeneous ABL development can also lead to mesoscale flows. The low-level jet (LLJ) is a phenomenon that has been identified in regions around the world, but most research has focused on the U.S. Southern Great Plains. A regional low-level jet, likely linked to the regional surface and ABL gradients, has been documented in the Baltimore region (Ryan 2004, Rabenhorst et al. 2014, Delgado et al. 2015, Weldegaber 2009). This regional LLJ is important in regional air quality and the development of convective storms. The causal mechanisms, predictability, and regional impacts (e.g., Lundquist and Mirocha 2008) of this regional LLJ have not yet been well documented. This understudied phenomenon is likely to be common to many coastal cities.

Coastal cities like Baltimore experience sea breezes (Simpson et al. 2008, Fan et al. 2020, Shepherd et al. 2010) that provide cooling (Yamamoto and Ishikawa 2020) and affect air quality (Seaman and Michelson 2000). The surface roughness of urban areas retards the inland movement of the sea breeze front (SBF) (Boucouvala and Bornstein 2003), while UHI convergence can enhance the SBF (Ferdiansyah et al. 2020). ABL cloud formation can be associated with the frontal lifting (Ferdiansyah et al. 2020). Surface pollutant concentrations are modified by convergent surface winds (Loughner et al. 2011), capping inversions (Darby et al. 2007), early morning offshore precursor transport (Ding et al. 2004), and recirculation of polluted air onshore (Wentworth et al. 2015). While sea breeze processes have been observed frequently, numerical weather models often struggle to simulate the marine ABL, perhaps because of limited ability to represent gradients in surface-atmosphere fluxes.

Sustained observations of the coast-urban-rural ABL system are needed to understand the impacts of regional ABL heterogeneity on the urban climate. Potential research questions include:

1. How much of the extreme heat experienced in an urban center is caused by urban land management versus upwind atmospheric conditions?
2. How is extreme heat modulated by ABL cloud cover and mesoscale flows?
3. Can urban-rural land management substantially alter the UHI and regional mesoscale flows such the LLJ and urban sea breeze, and what impacts would this have on the urban atmospheric environment?

1.2 Urban Atmospheric Composition

Activities and processes within urban areas perturb atmospheric composition of aerosols and trace gases (e.g., Jimenez et al. 2009, Anderson et al. 2021). Emissions of aerosols and trace gases in urban areas add to the regional burden of these constituents and can drive atmospheric chemical processes by introduction of reactive species. Direct primary emissions of aerosols from vehicles, cooking, and industrial sources add to urban burdens while reactive oxidative chemistry generates secondary reaction products such as organic aerosols and ozone, the strength of which varies by season (e.g., Jimenez et al. 2009, Avery et al. 2019). Summertime and wintertime atmospheric composition differs with higher concentrations of secondary aerosols and ozone in the summer and larger primary aerosol species burdens with lower ozone concentrations in the winter. New particle formation and growth of aerosols are important atmospheric processes (e.g., Kulmala et al. 2022) likely to have significant seasonal variability (e.g., Corral et al. 2022). Similarly, the formation of cloud condensation nuclei (CCN) from existing aerosol populations will vary by season (Padró et al. 2012). The chemical composition of aerosols and meteorological conditions affects the propensity of an aerosol particle to activate into CCN at a given supersaturation (e.g., Cubison et al. 2008, Duplissy et al. 2011).

The Baltimore region is complicated by spatially varying background atmospheric composition and ABL properties. Air entering Baltimore may have a primarily rural nature or can be modified by the Washington, D.C. metropolitan area. Bay breezes and LLJs may also alter the composition of the urban atmosphere.

Sustained observations are required to understand how seasonal and regional differences in emissions and oxidative atmospheric chemistry impact aerosol populations, composition, and CCN potential, and how these processes are modulated by the regional ABL, cloud, and radiative environment. Important scientific questions that need to be addressed include:

1. How does seasonal variability in atmospheric chemistry combined with regionally variable ABL dynamics influence regional and urban aerosol processes including atmospheric composition, CCN properties, and new particle formation and growth?
2. How much is urban atmospheric composition the product of local urban emissions versus advection from the neighboring environment?

   How much do mesoscale flows such as the coastal LLJ and the bay breeze modulate regional atmospheric composition?
3. To what extent does regional ABL cloud cover alter urban photochemistry?

1.3 Urban Radiation and Clouds

Simulating cloud cover at the coast-urban-rural boundary is a challenging problem that is critical to simulation of urban climate and atmospheric chemistry. Global climate and weather forecast models often struggle to portray cloud cover accurately, particularly in the case of shallow stratus and stratocumulus (Haiden and Trentmann 2016) – a shortcoming that is exacerbated in the vicinity of coast-urban-rural gradients due to the complex spatial variability in surface-atmosphere interactions and ABL development. Increased model resolution alone has not yielded improvements in the cloud simulations. A more fundamental understanding of the surface-atmosphere-cloud system is needed.

The urban environment influences microphysical aspects of clouds, leading to coast-urban-rural contrasts in cloud coverage (Theeuwes et al. 2019), cloud microphysical properties, precipitation, and lightning (Burke and Shepard 2023). Spatial gradients in surface fluxes will alter cloud dynamics since surface fluxes and ABL depth regulate the width, entrainment rates, and updraft vigor of the ABL eddies that drive convective overturning in the cloud layer (Lei et al. 2008). These connections between aerosols, surface-atmosphere fluxes and ABL gradients, and cloud dynamics are relevant to a range of patterns of cloud organization, including stratocumulus, shallow cumulus, congestus, and deep convection.

Cloud distributions are documented via satellite, and cloud depth and fractional coverage routinely observed via ceilometer networks, but detailed observations of the interactions among ABL dynamics, atmospheric composition, and the resulting physical properties of cloud cover are much more limited. The AMF1 deployment to the Baltimore region will provide a uniquely detailed view of the both cloud distributions and depths, and their interactions with the entire surface-ABL-composition-cloud system (Figure 4.1). Scientific questions that will be addressed include:

1. How does the coast-urban-rural landscape, and the associated gradients in ABL and aerosol properties, lead to variability in cloud characteristics (e.g., fractional cover, base, width, convective strength, water content)?
2. How do these patterns in cloud cover feedback influence urban climate and atmospheric chemistry?
3. How much do mesoscale flows such as the coastal LLJ and the bay breeze contribute to regional cloud formation?

1.4 Urban Precipitation

The urban environment impacts the spatial distribution of convective precipitation, through the development of a localized UHI (Shepherd et al. 2002, Shepherd and Burian 2003, Liu and Niyogi 2020, Choi and Lee 2021), enhanced convergence due to changes in surface roughness (Thielen et al. 2000), bifurcation of precipitating storms due to the urban canopy (Bornstein and Lin 2000, Niyogi et al. 2011), and the production of CCN (Diem and Brown 2003, Molders and Olson 2004). A city of 25-km spatial footprint or greater has been found to modify convective rains (Schmid and Niyogi 2013). Annual and warm-season rainfall anomalies, for example, were observed by the Tropical Rainfall Measuring Mission (TRMM) over and downwind of Houston, Texas (Shepherd and Burian 2003), likely due to the UHI and local sea breeze circulations. In contrast, Dixon and Mote (2003) showed that moisture convergence associated with the urban environment, rather than the UHI, was the dominant mechanism supporting convective initiation over Atlanta, Georgia, resulting in a diurnal peak in precipitation after midnight. Urban aerosols continue to be one of the most poorly understood aspects of the urban rainfall anomaly (van den Heever and Cotton 2007, Schmid and Niyogi 2017).

Observations also indicate that the initiation and evolution of convective precipitation are strongly modulated by coastal ABL heterogeneities. Convection may be initiated by kinematic and/or moisture convergence along a land-sea boundary, ascent driven by a moving SBF, or ascent driven by gravity waves. The convection initiation (CI) mechanism determines the source region of air ingested into the storm updraft (land ABL, marine ABL, elevated free troposphere), and thus the microphysical, thermodynamic, and kinematic properties of the updraft air, which can influence precipitation production and storm lifetime. For mature organized storms that develop inland and move offshore, interaction with a coastal ABL boundary can result in storm weakening (Soderholm et al. 2016, Lombardo and Kading 2018), intensification (Lombardo 2020, Wu and Lombardo 2021), a discrete propagation (Lombardo 2020), or a change in storm morphology (Hartigan et al. 2021), impacting precipitation intensity, coverage, and duration.

The physical processes driving coastal CI and storm evolution have been primarily studied through an idealized numerical framework (Baker et al. 2001, Fovell 2005, Lombardo and Kading 2018, Lombardo 2020, Hartigan et al. 2021, Wu and Lombardo 2021, Fu et al. 2022). A limited number of observational studies exist (Kingsmill 1995, Soderholm et al. 2016). Much of what we have learned about coastal CI and storm evolution is from highly idealized numerical environments, initialized with a single atmospheric profile, a homogeneous marine airmass, and uniform coastlines. Many of the additional physical processes we hypothesize may govern coastal urban precipitation have yet to be observed. Existing studies of urban precipitation patterns yield conflicting findings in observational versus numerical studies (Liu and Niyogi 2019). Models often underestimate the mean impact of urban rainfall modification and suggest spatial patterns of precipitation enhancement that conflict with observations.

Sustained observations of the multiple factors governing the development of precipitation (Figure 1) across the heterogeneous surface created by urbanization are needed to establish a quantitative, process-based understanding of urban precipitation. Questions to be addressed include:

1. What are the important physical processes governing both convection initiation and the modification of mature organized convective storms (i.e., precipitation hotspots) across the Baltimore urban-coastal environment?

2. Are there atmospheric features (e.g., marine ABL, UHI) not captured in mesoscale/operational models that limit the successful prediction of regional convective storm behavior?
3. How much do mesoscale flows such as the coastal LLJ and the bay breeze contribute to convective storm initiation?
4. How does the UHI alter both convective precipitation and winter storms?
5. How does the impact of urban aerosols on CCN and storm development change under differing regional pollution regimes?
6. Do the impacts of coast-urban-rural ABL gradients on urban precipitation vary depending on the morphology of precipitating systems (e.g., a squall line versus individual convective cells)?

1.5 General Questions

For all topics outlined above, we wish to extend our understanding of these processes to advances in ESMs of the coast-urban-rural system. Thus we also ask:

1. How well do current ESMs represent these coast-urban-rural gradients and their impacts on coastal urban climate, air quality and precipitation?
2. Do our observations and model-data comparisons reveal processes that are either poorly captured or entirely missing (e.g., marine ABL, UHI, coastal LLJ, cloud-aerosol feedbacks) in current ESMs?

We also want to use the understanding gained to help cities respond to the challenges of climate change. Thus we also ask:

1. What are the implications of our findings for climate change adaptation and mitigation measures being considered for coastal urban centers?
2. Does our improved understanding of the coastal-urban-rural atmospheric environment and its interactions inform how potential land management, and industrial and energy system changes are likely to impact the urban atmospheric environment?

We hypothesize that accurate and precise quantification of the Baltimore atmospheric environment and its response to changing climate, energy and industrial systems, and land management depends on accurate and precise understanding of the temporally varying spatial gradients in surface-atmosphere fluxes, and the interactions of the coupled atmospheric system (Figure 1). Alternatively stated, we propose to determine the degree to which quantification of Baltimore’s atmospheric environment:

1. Depends on feedback in the surface-ABL-cloud-composition atmospheric system;
2. Depends on the surrounding environment versus determined primarily by the nature of the urban system.

Understanding this integrated coastal-urban-rural system quantitatively and with good accuracy and precision is critical to informing climate adaptation and mitigation efforts in coastal cities.

The BSEC is deploying long-term measurements of the urban atmospheric boundary layer and land-atmosphere interactions in the city of Baltimore but does not have the resources to encompass the full complexity of the interactive atmospheric system (Figure 1) within the city, or the ability to monitor the heterogeneity of the atmospheric environment surrounding the city. Thus, the BSEC instruments alone cannot provide the full suite of data needed for disaggregation of the multiple influences on the Baltimore atmospheric environment. These scientific objectives and current limits to our observational resources motivates our request for the AMF1.

We will address the observational shortcomings noted above by studying the entire linked atmospheric system (Figure 1) at four sites representing Baltimore and its three major upwind environments (Figure 2). BSEC observations in the city do not include extensive measurements of clouds, radiation, and their relationship to radiation and precipitation. The AMF1 deployment to Baltimore will provide an unparalleled, four-seasons set of continuous observations of the fully coupled atmospheric system (Figure 1) within a major mid-latitude urban center. Key environments surrounding Baltimore and proposed ancillary sites include the rural landscapes of the mid-Atlantic region, Chesapeake Bay, and the Washington, D.C. metropolitan area. As these interactions are likely to vary with season and time of day, a full-year deployment will be requested.

2.0 Scientific Objectives

Our general objective is to determine the dependence of Baltimore's atmospheric environment (thermodynamics, cloud properties, surface radiation, aerosols and atmospheric composition, winds, precipitation) on the urban system versus the environments surrounding the city. More specifically, we aim to:

1. Quantify the relative importance of upwind conditions and mesoscale flows versus urban land-atmosphere interactions on Baltimore's ABL properties (including urban microclimate) across seasons and weather conditions.
2. Quantify the relative importance of urban land-atmosphere interactions and pollutant emissions versus upwind boundary conditions and mesoscale flows on Baltimore's atmospheric composition and aerosol characteristics.
3. Quantify the impact of urban atmospheric composition, aerosol characteristics, and ABL development in the coast-urban-rural system on urban ABL cloud cover and radiation. Quantify cloud radiative feedback on urban atmospheric composition and climate.
4. Quantify the impact of the coast-urban-rural landscape on the characteristics of urban precipitation events.

Significance. Addressing these research objectives will deepen our understanding of the coupled surface-ABL-composition-cloud-radiation-precipitation system (Figure 1) in the coast-urban-rural environment typical of many mid-latitude coastal cities. We will also quantify how much Baltimore alters its own atmospheric environment, the degree to which urban management can impact that environment in the future, and the ability of our numerical modeling systems to reproduce these interactions and thus guide urban adaptation and mitigation efforts. These are critically important outcomes for urban climate prediction, adaptation, and management. Our findings for Baltimore should be transferable to many mid-latitude cities around the world.

Significance for the BSEC urban IFL. The AMF1 deployment will add three key elements to BSEC. First, it will enable us to discern with confidence the role of the urban fluxes and emissions on the Baltimore atmospheric environment and to disaggregate this from the impact of surrounding regions on Baltimore's atmospheric environment. This understanding, combined with improved ability to simulate this regional environment in ESMs, will yield critical improvements in our ability to inform urban climate mitigation and adaptation pathways. Second, the addition of a much more comprehensive set of observations of urban clouds and radiation will broaden our ability to study the fully coupled urban atmospheric system (Figure 1). Third, this deployment will expand our research team and the depth of investigation that will be devoted to these critical topics.

3.0 Measurement Strategies

3.1 Overview

3.1.1 Science Traceability Matrix

Each research objective calls for measurements that enable this objective. This overall measurement strategy is summarized in our science traceability matrix, Table 1.

3.1.2 Deployment Plan

The AMF1 core site and two ancillary sites will be deployed in and around Baltimore (Figure 2) for one calendar year, December, 2024 through November, 2025. These observations will complement the BSEC and other regional atmospheric observations to construct a multi-site observatory (ARM Decadal Vision Theme 1.5) that will document the degree to which the Baltimore atmospheric environment is determined by the characteristics of the urban system alone versus a product of the heterogeneous surface conditions surrounding the city.

3.1.3 Multi-Site Network Design

The proposed four-node network (Figure 2) will create four atmospheric boundary-layer observatories (Baltimore, Rural, Bay, Beltsville), three atmospheric composition and aerosol observatories (Baltimore, Rural, Beltsville), and one cloud/radiation/precipitation observatory (Baltimore). This network will observe the land-atmosphere system (Figure 1) that is the Baltimore atmospheric environment (Baltimore/Core), and to observe upwind influence from the three major environments surrounding the city - Rural Urban (Beltsville-D.C.) and Bay. During IOPs, thermodynamic profiling will be enhanced at the Rural and Bay ancillary sites and atmospheric composition instruments will be deployed at the Bay/ancillary and Beltsville sites. This array satisfies the requirements of the Science Traceability Matrix for Upwind Rural (Rural), Upwind Urban (Beltsville-D.C.), and Bay study sites in addition to the Urban observatory (Baltimore/Core).

3.1.4 Collaborative Resources

This network builds upon extensive existing observations both in the Baltimore (BSEC, MSU, UMBC) and at the Beltsville-D.C. site (HU, MDE, NOAA).

3.1.5 Regional Resources

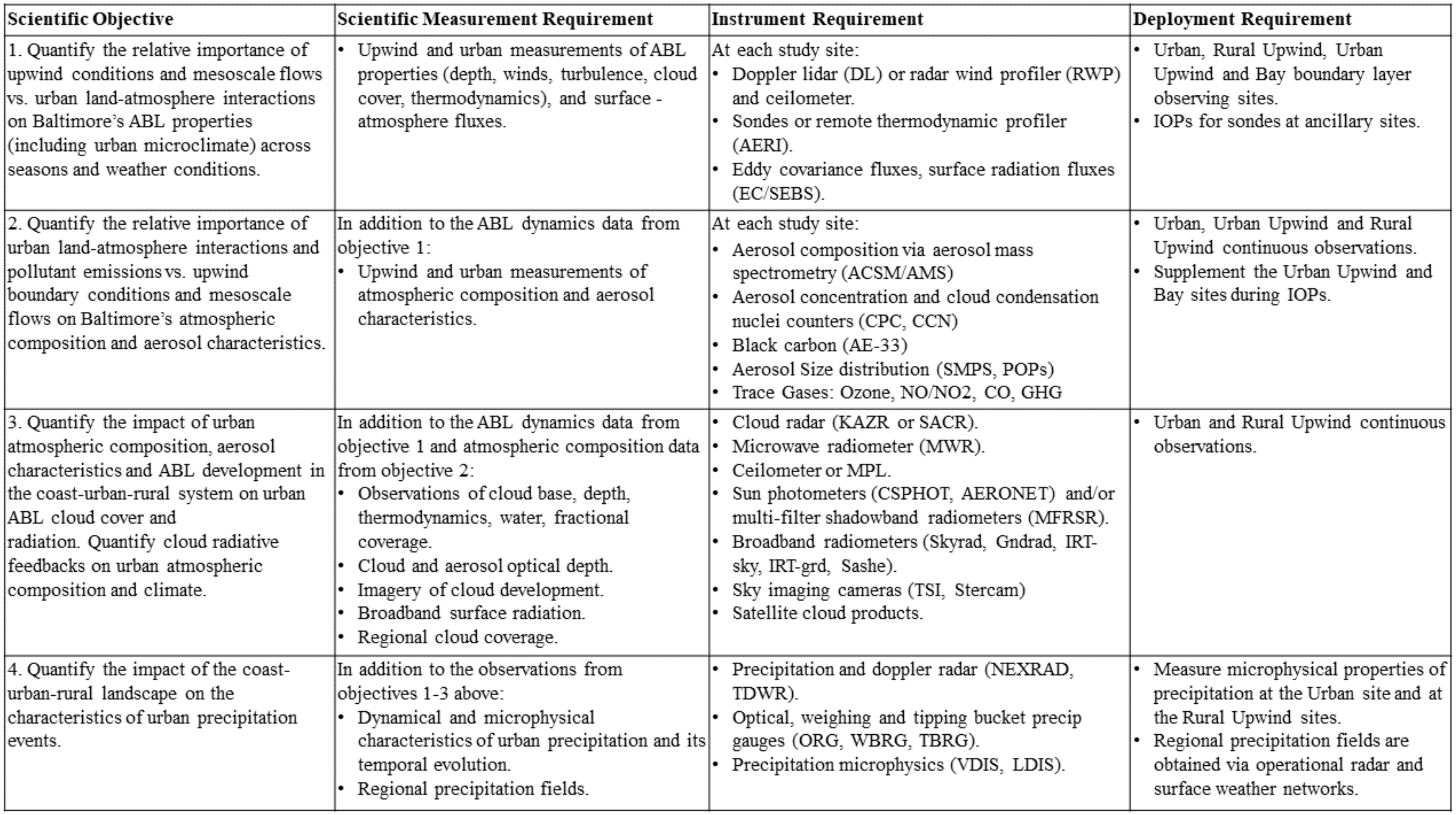
This network is embedded within (Figure 2) a radar wind profiling (Horn Point, Beltsville, Piney Run) network operated by the MDE, and the regional network of National Weather Service operational radars (Next-Generation Weather Radar – NEXRAD). The proposed network is also co-located with (not pictured) the NIST Northeast Corridor urban greenhouse gas testbed program, the Unified Ceilometer Network (UCN), National Aeronautics and Space Administration (NASA) Goddard’s Aerosol Robotic Network (AERONET), a new surface mesonet being deployed by MDE, and several AmeriFlux eddy covariance flux towers. Our research activities will endeavor to include NIST, NOAA (Global Monitoring Laboratory, Chemical Sciences Laboratory and Atmospheric Research Laboratory), UCN, NASA Goddard Institute for Space Studies, AmeriFlux, and MDE scientists. This extensive, multi-instrument regional network of networks provides a remarkable mesoscale setting for the AMF1 deployment.

3.1.6 Temporal Nature of the Data Collection

All of the scientific objectives will be studied as a function of season, time of day, and weather condition. Continuous deployment of all instruments for one annual cycle is requested. A full year of observations will enable us to quantify the seasonal variability of the impacts of the heterogeneous system on the urban atmosphere. There will be strong seasonal differences in synoptic weather, surface conditions, atmospheric stability, cloud characteristics, and atmospheric composition and processing that we aim to capture with this deployment.

IOPs. Two two-week IOPs are planned, one in midsummer and in midwinter. These IOPs will enable enhanced sampling during these seasonal extremes. The IOPs are long enough to sample a few synoptic cycles. During the IOPs, we will launch rawinsonde from the Rural ancillary site and have requested tethered balloon operations from a site representative of air over Chesapeake Bay. During IOPs, collaborators will measure trace gases and aerosols at the Beltsville and Chesapeake Bay sites for more complete regional characterization of atmospheric composition.

Table 1. Science traceability matrix for CoURAGE. Note that temporal deployment requirements are addressed in the text.



Scientific Objective	Scientific Measurement Requirement	Instrument Requirement	Deployment Requirement
1. Quantify the relative importance of upwind conditions and mesoscale flows vs. urban land-atmosphere interactions on Baltimore's ABL properties (including urban microclimate) across seasons and weather conditions.	• Upwind and urban measurements of ABL properties (depth, winds, turbulence, cloud cover, thermodynamics), and surface - atmosphere fluxes.	At each study site: • Doppler lidar (DL) or radar wind profiler (RWP) and ceilometer. • Sondes or remote thermodynamic profiler (AERI). • Eddy covariance fluxes, surface radiation fluxes (EC/SEBS).	• Urban, Rural Upwind, Urban Upwind and Bay boundary layer observing sites. • IOPs for sondes at ancillary sites.
2. Quantify the relative importance of urban land-atmosphere interactions and pollutant emissions vs. upwind boundary conditions and mesoscale flows on Baltimore's atmospheric composition and aerosol characteristics.	In addition to the ABL dynamics data from objective 1: • Upwind and urban measurements of atmospheric composition and aerosol characteristics.	At each study site: • Aerosol composition via aerosol mass spectrometry (ACSM/AMS) • Aerosol concentration and cloud condensation nuclei counters (CPC, CCN) • Black carbon (AE-33) • Aerosol Size distribution (SMPS, POPs) • Trace Gases: Ozone, NO/NO2, CO, GHG	• Urban, Urban Upwind and Rural Upwind continuous observations. • Supplement the Urban Upwind and Bay sites during IOPs.
3. Quantify the impact of urban atmospheric composition, aerosol characteristics and ABL development in the coast-urban-rural system on urban ABL cloud cover and radiation. Quantify cloud radiative feedbacks on urban atmospheric composition and climate.	In addition to the ABL dynamics data from objective 1 and atmospheric composition data from objective 2: • Observations of cloud base, depth, thermodynamics, water, fractional coverage. • Cloud and aerosol optical depth. • Imagery of cloud development. • Broadband surface radiation. • Regional cloud coverage.	• Cloud radar (KAZR or SACR). • Microwave radiometer (MWR). • Ceilometer or MPL. • Sun photometers (CSPHOT, AERONET) and/or multi-filter shadowband radiometers (MFRSR). • Broadband radiometers (Skyrad, Gndrad, IRT-sky, IRT-grd, Sashe). • Sky imaging cameras (TSI, Stercam) • Satellite cloud products.	• Urban and Rural Upwind continuous observations.
4. Quantify the impact of the coast-urban-rural landscape on the characteristics of urban precipitation events.	In addition to the observations from objectives 1-3 above: • Dynamical and microphysical characteristics of urban precipitation and its temporal evolution. • Regional precipitation fields.	• Precipitation and doppler radar (NEXRAD, TDWR). • Optical, weighing and tipping bucket precip gauges (ORG, WBRG, TBRG). • Precipitation microphysics (VDIS, LDIS).	• Measure microphysical properties of precipitation at the Urban site and at the Rural Upwind sites. • Regional precipitation fields are obtained via operational radar and surface weather networks.

3.2 Observational Requirements by Discipline

We next describe the observations deployed to satisfy each scientific focus area.

3.2.1 ABL Observatories

Heterogeneous development of the ABL is a central focus of this study (objective 1) and a building block of all of the project hypotheses and objectives. Each of our four ABL observatories is designed to provide continuous observations of essential ABL characteristics. Observations required (Table 1) include ABL depth, winds, turbulence, cloud cover, and thermodynamics, and the surface-atmosphere fluxes that contribute to these ABL properties. The ABL instrument requirements (Table 1) include a lidar (Doppler or ceilometer) to observe ABL depth, cloud base height and cloud fraction; a wind profiler (Doppler lidar and/or radar wind profiler) to measure horizontal wind profiles and profiles of atmospheric turbulence, and a thermodynamic profiling system (balloon-borne sonde or atmospheric emitted radiance interferometer [AERI]) to measure temperature, humidity, and pressure as a function of altitude. Surface-based observations of sensible and latent heat flux, momentum flux, and incoming and outgoing solar and infrared radiation characteristic of the region are needed to diagnose the drivers of ABL development.

3.2.2 Atmospheric Composition Observatories

Heterogeneous atmospheric composition is a second building block of the project (objective 2), and a critical contribution to our studies of clouds and precipitation. Each of our three atmospheric composition observatories is designed to provide continuous observations of atmospheric composition. Two observational nodes (Rural, Beltsville) are located in regions representative of air that is likely to be advected into the city. Observations required (Table 1) include aerosol number, size distribution, bulk composition including black carbon, CCN activity, and trace gases: Ozone, NO, NO_2, CO, CO_2, and methane. Measurements of these species allow us to compare regional and urban aerosol populations and composition to provide insight into emission, processing, and impacts of the urban area on atmospheric composition. Linking aerosol composition to trace gases including ozone and NO_x will be important for understanding the near-field chemical processing of regional and urban aerosols. CCN measurements in both rural and urban environments will be key to linking how the urban environment modifies the propensity of an aerosol population to form cloud condensation nuclei. The Bay will also serve as an atmospheric composition observatory during IOPs when it hosts Co-I DeCarlo's mobile laboratory (section 3.7) and atmospheric composition instruments on the TBS (section 3.6).

3.2.3 Cloud and Radiation Observatories

Quantifying the impacts of regional ABL and atmospheric composition heterogeneity on urban cloud cover and radiation, and cloud feedback to urban climate and atmospheric composition, is a major objective of this study (objective 3). To that end, the two cloud and radiation observatories (Baltimore, Rural) will provide continuous observations of clouds and radiation, enabling study of both the impact of the regional environment on Baltimore urban clouds and a comparison to conditions in the rural upwind environment. Observations required (Table 1) include a cloud radar, lidar-based cloud sensors (ceilometer or MPL), a microwave radiometer, ground-based radiometers to measure broadband radiation and aerosol optical depth, and sky imaging camera. All of these measurements will be available at the Core site and all but the cloud radar will be present at the Rural site. Many of these instruments and observations will also be available at the Beltsville site and some at the Bay site. We also request the SatCorps Geostationary satellite cloud macro- and microphysical property retrievals (https://cloudsway2.larc.nasa.gov) to inform the spatial distribution of regional cloud cover, complementing the detailed observations of cloud and radiation properties at the observatories.

3.2.4 Precipitation Observations

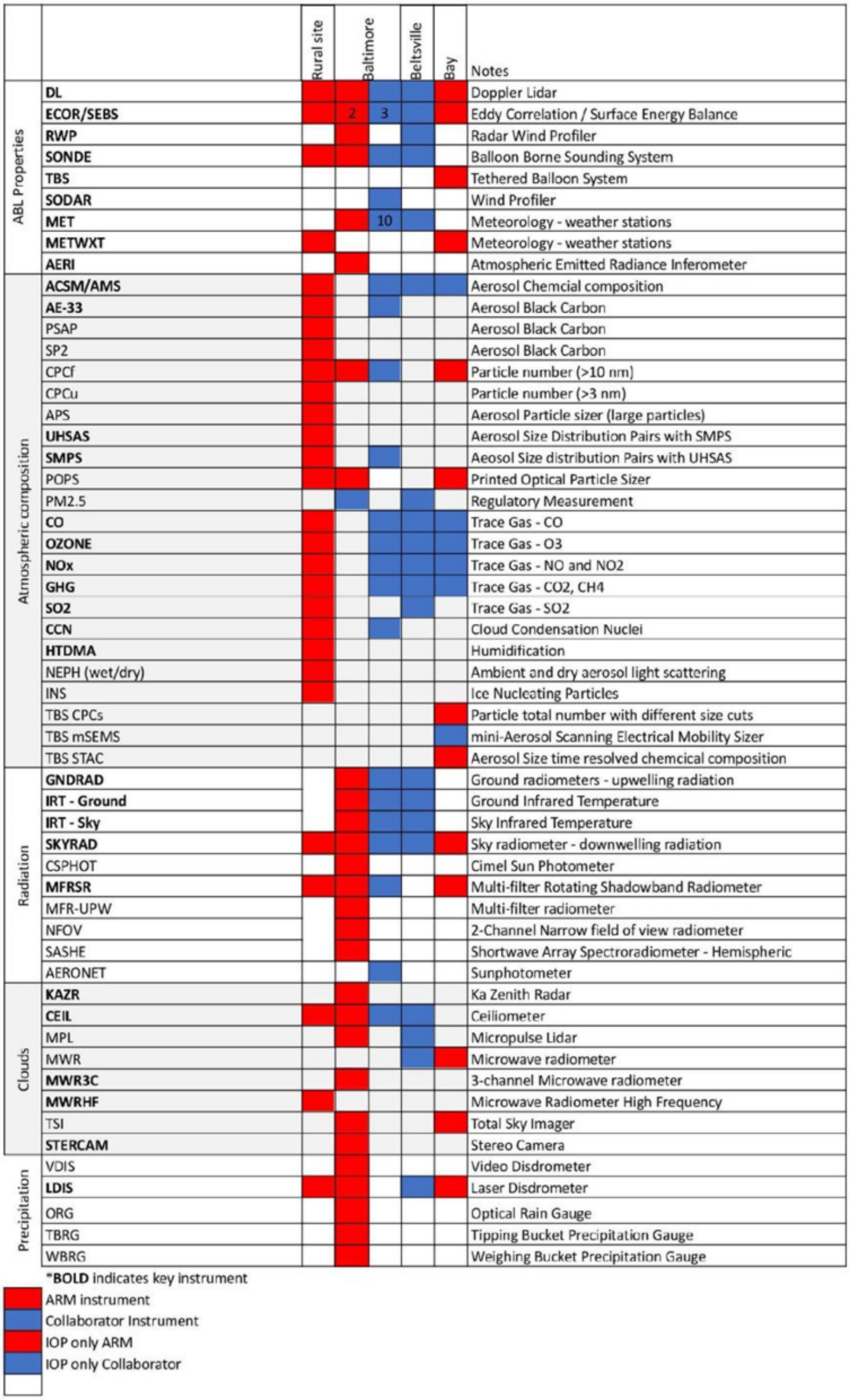
Understanding how the regional environment impacts urban precipitation (objective 4) is the final major objective of this investigation. All four sites will monitor precipitation microphysics with the most detail available at the Core facility in Baltimore. This objective also relies significantly on spatially distributed measurements of precipitation from other sources. Additional observations required (Table 1) include radar reflectivity from the S-band NEXRAD owned and operated by the NWS, FAA, and Air Force and C-band terminal Doppler weather radars (TDWR) owned and operated by the FAA, NEXRAD radial velocity data, and operational precipitation accumulation from 1) the NOAA Automated Surface Observing System (ASOS) rain gauge data; 2) the MDE state mesonet, and 3) a multi-site urban precipitation network within Baltimore (BSEC).

3.3 Nodes of CoURAGE: Observation Sites, Scientific Objectives, and Instrumentation

This section provides the logic and layout of each of the four observational nodes (Figure 2) to be created for CoURAGE. The AMF1 Core Facility will be deployed to the Clifton Park site owned by MSU close to downtown Baltimore (Figures 2, 3). Two ancillary sites will be deployed (Figure 2), one in rural Maryland and another on Kent Island. These deployments will be complemented by substantial existing observational resources in Baltimore, mostly supported by the BSEC urban integrated field laboratory, and a well-instrumented long-term observation site in Beltsville, Maryland maintained by HU and the MDE. We refer to each site as an observational node.

Table 2 includes ARM and collaborators’ instruments that make up the four nodes. The table is organized according to the primary scientific application (ABL, atmospheric composition, clouds, radiation, precipitation) of the instruments. We elaborate on the objectives for the instruments at each of the four observation nodes in the following text, delineating ARM versus collaborator instrumentation at each node.

Table 2. Instrumentation for ARM and collaborators organized by scientific application across four observation nodes.



		Rural site	Baltimore		Beltsville	Bay	Notes
ABL Properties	**DL**	🟥	🟥	🟦	🟦	🟥	Doppler Lidar
	ECOR/SEBS	🟥	🟥 2	🟦 3	🟦	🟥	Eddy Correlation / Surface Energy Balance
	RWP		🟥		🟦		Radar Wind Profiler
	SONDE	🟥	🟥	🟦	🟦		Balloon Borne Sounding System
	TBS					🟥	Tethered Balloon System
	SODAR			🟦			Wind Profiler
	MET		🟥	🟦 10	🟦		Meteorology - weather stations
	METWXT	🟥				🟥	Meteorology - weather stations
	AERI		🟥				Atmospheric Emitted Radiance Inferometer
Atmospheric composition	**ACSM/AMS**	🟥		🟦	🟦	🟦	Aerosol Chemcial composition
	AE-33	🟥		🟦			Aerosol Black Carbon
	PSAP	🟥					Aerosol Black Carbon
	SP2	🟥					Aerosol Black Carbon
	CPCf	🟥	🟥	🟦		🟥	Particle number (>10 nm)
	CPCu	🟥					Particle number (>3 nm)
	APS	🟥					Aerosol Particle sizer (large particles)
	UHSAS	🟥					Aerosol Size Distribution Pairs with SMPS
	SMPS	🟥		🟦			Aeosol Size distribution Pairs with UHSAS
	POPS	🟥	🟥			🟥	Printed Optical Particle Sizer
	PM2.5		🟦		🟦		Regulatory Measurement
	CO	🟥		🟦	🟦	🟦	Trace Gas - CO
	OZONE	🟥		🟦	🟦	🟦	Trace Gas - O3
	NOx	🟥		🟦	🟦	🟦	Trace Gas - NO and NO2
	GHG	🟥		🟦	🟦	🟦	Trace Gas - CO2, CH4
	SO2	🟥			🟦		Trace Gas - SO2
	CCN	🟥		🟦			Cloud Condensation Nuclei
	HTDMA	🟥					Humidification
	NEPH (wet/dry)	🟥					Ambient and dry aerosol light scattering
	INS	🟥					Ice Nucleating Particles
	TBS CPCs					🟥	Particle total number with different size cuts
	TBS mSEMS					🟦	mini-Aerosol Scanning Electrical Mobility Sizer
	TBS STAC					🟥	Aerosol Size time resolved chemcical composition
Radiation	**GNDRAD**		🟥	🟦	🟦		Ground radiometers - upwelling radiation
	IRT - Ground		🟥	🟦	🟦		Ground Infrared Temperature
	IRT - Sky		🟥	🟦	🟦		Sky Infrared Temperature
	SKYRAD	🟥	🟥	🟦	🟦	🟥	Sky radiometer - downwelling radiation
	CSPHOT		🟥				Cimel Sun Photometer
	MFRSR	🟥	🟥	🟦		🟥	Multi-filter Rotating Shadowband Radiometer
	MFR-UPW		🟥				Multi-filter radiometer
	NFOV		🟥				2-Channel Narrow field of view radiometer
	SASHE		🟥				Shortwave Array Spectroradiometer - Hemispheric
	AERONET			🟦			Sunphotometer
Clouds	**KAZR**		🟥				Ka Zenith Radar
	CEIL	🟥	🟥	🟦	🟦		Ceiliometer
	MPL		🟥		🟦		Micropulse Lidar
	MWR				🟦	🟥	Microwave radiometer
	MWR3C		🟥				3-channel Microwave radiometer
	MWRHF	🟥					Microwave Radiometer High Frequency
	TSI		🟥			🟥	Total Sky Imager
	STERCAM		🟥				Stereo Camera
Precipitation	VDIS		🟥				Video Disdrometer
	LDIS	🟥	🟥		🟦	🟥	Laser Disdrometer
	ORG		🟥				Optical Rain Gauge
	TBRG		🟥				Tipping Bucket Precipitation Gauge
	WBRG		🟥				Weighing Bucket Precipitation Gauge

*__BOLD__ indicates key instrument

🟥 ARM instrument

🟦 Collaborator Instrument

🟥 IOP only ARM

🟦 IOP only Collaborator

⬜

3.3.1 Baltimore Urban Node/Core Facility

The Clifton Park site close to downtown Baltimore will host the ARM core facility (Figure 3). This site, owned by BSEC partner MSU, will enable the urban deployment of AMF1. The AMF1 Core Facility will enhance the long-term observations that are part of the BSEC urban integrated field laboratory.

The AMF1 deployment will greatly enhance the cloud and radiation, and precipitation microphysics, measurements available in Baltimore, in addition to expanding the ABL profiling, surface flux, air quality, and microclimate measurements that are part of BSEC. The core site measurements will document the full atmospheric environment of the city including clouds (e.g., KAZR, MWR, CEIL, sondes), radiation, precipitation, and ABL properties (e.g., AERI, Doppler lidar [DL], eddy covariance/surface energy balance system [EC/SEBS]).

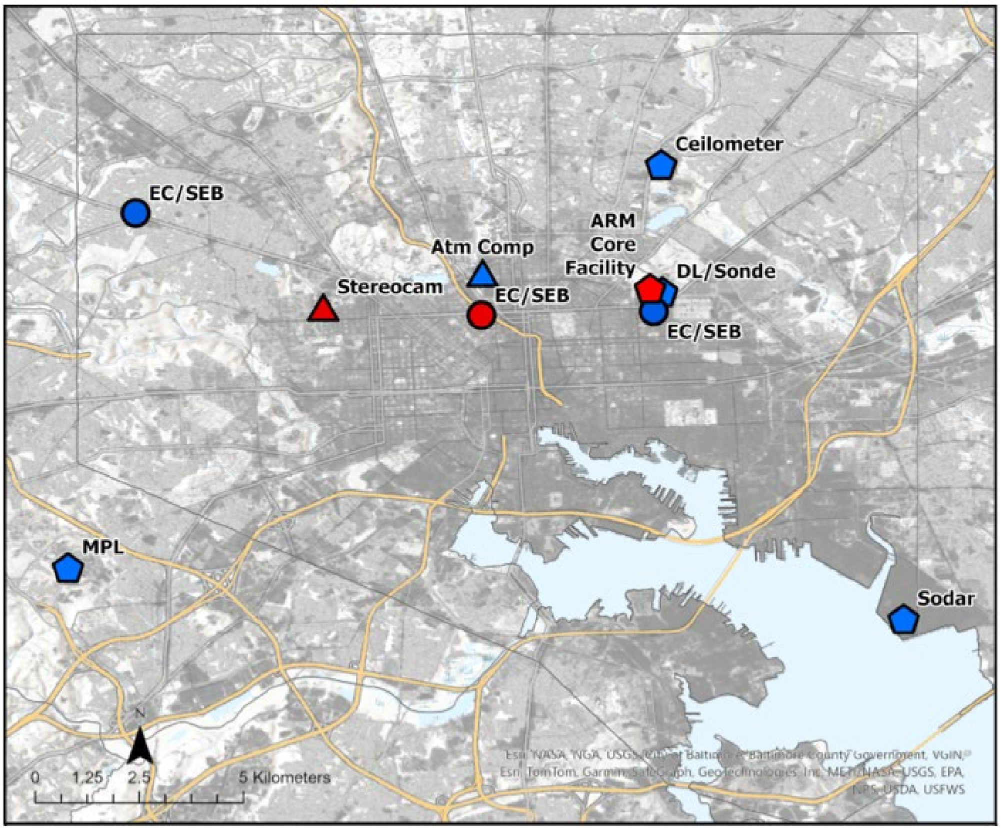


Figure 3. The AMF1 (red pentagon) deployed at the Clifton Park site owned by MSU, will complement an array of BSEC and partner long-term observational resources (blue) available in Baltimore. We also request downtown deployment of two EC/SEB systems from ARM (red circle) and STERCAM (red triangle) potentially deployed on the MSU campus to overlook the Clifton Park main site. These observations are complemented by a BSEC-funded network of weather and air quality stations spread across the city (not shown). The background shading represents the fraction of impervious surface.

Table 2 lists the suite of AMF1 core Facility observations, most of which will be located at Clifton Park (Figure 3). The STERCAM will be deployed away from the Main facility where it can view convective clouds forming over the Main facility, perhaps at Coppin State University. Two EC/SEBS stations will be deployed on building tops in downtown Baltimore. The Maryland Institute College of Arts and the

Peabody campus of Johns Hopkins are prospective sites for the EC/SEB instruments. Approximate locations are shown in Figure 3. These flux measurements in the urban center will complement the BSEC residential and low-stature vegetation flux measurements and will support investigation of anthropogenic heat and moisture fluxes.

AMF1 will supplement BSEC observations. BSEC observational assets include (Figure 3, Table 2) a HALO XR scanning Doppler lidar, an atmospheric composition "supersite," similar in many ways to the ARM Aerosol Observing System (AOS), to be deployed at a location close to Clifton Park but where indoor measurements can also be collected, a low-cost rawinsonde system (Windsonde) dedicated to weekly balloon launches, two EC/SEBS flux towers (instrumented communications towers) operating in two urban residential neighborhoods typical of a large fraction of Baltimore neighborhoods, and a sodar providing lower atmospheric wind profiles at the coast, intended to quantify bay breeze events. We also have one low-stature EC/SEB station running in turfgrass at Clifton Park. BSEC investigators have deployed hydrologic and ecosystems measurements at locations designed to be presentative of urban hydrology and vegetation. These BSEC-supported observations are complemented by a ceilometer at MSU and a micropulse lidar (MPL) at the UMBC campus.

BSEC also includes an urban observation network (Figure 4) designed to document the environment experienced by city residents and to evaluate urban atmospheric environmental models. These measurements are critical *since air quality, weather, and flooding are the critical variables that we endeavor to simulate well to show that a new generation of ESMs can serve the needs of our urban populations*. A neighborhood-level network of more than 20 (10 research-grade, 10+ citizen science-grade) weather stations is mostly operational. We are gathering data on urban flooding from both BSEC and city data sources. A 40-node, low-cost air quality sensor network is operational across the city. These observations complement the "process-focused" observations (surface fluxes, ABL depth, radiation, cloud cover) that will be observed by CoURAGE and that our models must simulate well to reproduce neighborhood flooding, air quality, and weather with good fidelity.

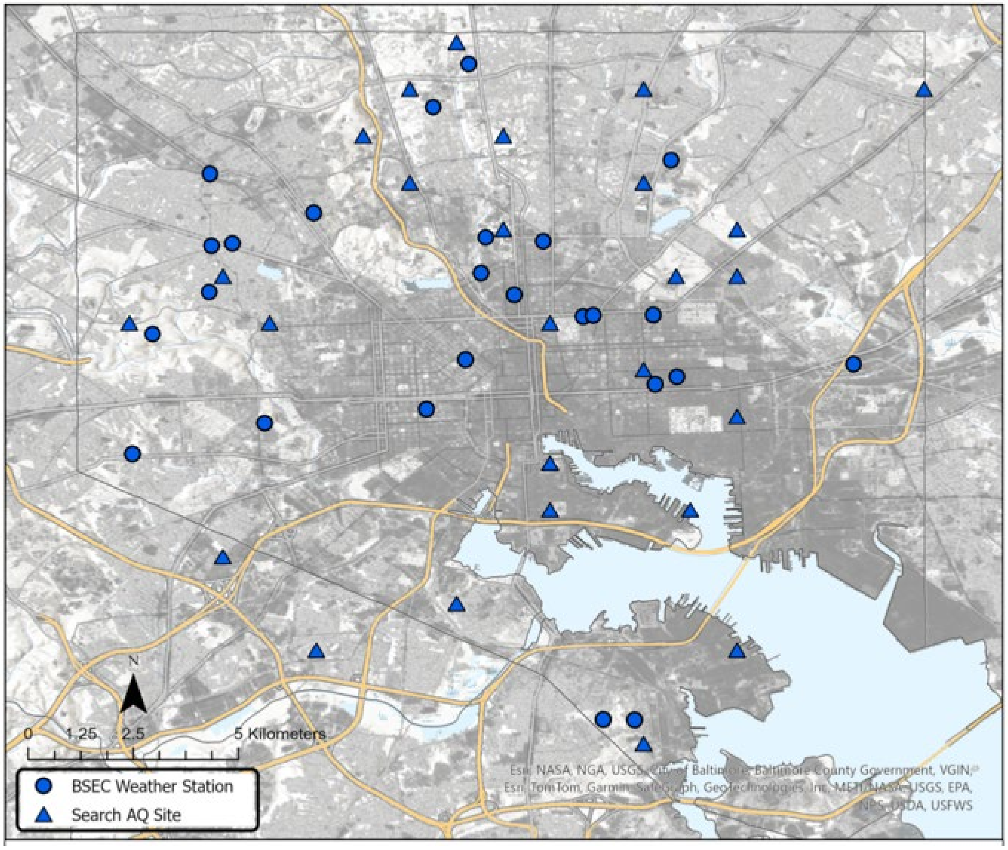


Figure 4. BSEC surface weather stations (blue circles) deployed throughout Baltimore to date complement an existing array of Search AQ sites (blue triangles) managed by JHU.

3.3.2 Rural Node/Ancillary Site

One AMF1 ancillary site will be deployed at a rural location to the northwest of Baltimore (Figure 2). This location, east of the first ridge of the Appalachian Mountains, is intended to be representative of the rural atmosphere to the northwest of Baltimore. This position will also aid in our study of the regional LLJ which is encountered east of the mountains.

This node will have observations comparable to the Baltimore Core site with the exception of a cloud radar. The AOS, typically located at the Core facility, will be deployed at this rural background site. This will create matched atmospheric composition measurements with the BSEC atmospheric composition facility in Baltimore. This rural/urban contrast in atmospheric composition is a key component of our study.

Some cloud observational assets not typically located at an ancillary site will be deployed to observe the contrast in rural and urban clouds, precipitation, and radiation. The cloud profiling observations to be deployed at this site include a microwave radiometer and a ceilometer. These instruments, in combination with AMF1 disdrometer and radiation data, will establish a clouds and radiation observatory for the rural environment.

The site will host typical ABL and tropospheric profiling instruments: a DL to provide continuous wind profiles, turbulence and ABL depth measurements, and one EC/SEBS station to be deployed over an agricultural field, since much of the terrain immediately upwind of Baltimore is agricultural. This single flux tower will be supplemented by several forest and agricultural flux towers operating in the region and contributing data routinely to AmeriFlux. Sondes will be launched from the rural site during IOPs to expand regional thermodynamic profiling. We note that outside of the IOPs, the Dulles NWS sounding site (IAD) is likely to be representative of the rural background conditions (and this assertion can be tested with ARM IOP soundings).

3.3.3 Chesapeake Bay Node/Ancillary Site

A second AMF1 ancillary site will be deployed at the south end of Kent Island in Chesapeake Bay (Figure 2) and will characterize the bay atmosphere. The location on the southern end of the island is nearly surrounded by the bay and the profilers will sample the bay atmosphere in all cases save for northeasterly winds coming down the length of the island. ABL observations will be supplied with a DL and EC/SEB system. The EC/SEBS sensor will be located on a pier over the water to capture, as much as possible, fluxes between the bay and the atmosphere. A microwave radiometer will add cloud profiling capabilities, a laser disdrometer will monitor precipitation properties and incoming radiation measurements, and a total sky imager will document cloud and radiation conditions over the bay.

The bay will also serve as an atmospheric composition observatory during IOPs, but an alternative location is required. We have requested (section 3.6) the ARM TBS to be deployed to the bay for IOPs. The TBS will include thermodynamic and wind profiling measurements and will carry aerosol observations. The TBS will be complemented by Co-I DeCarlo’s mobile laboratory (section 3.7) including aerosol concentration, size distribution, and trace gas measurements. Airspace restrictions require an alternative deployment site for the TBS farther from Washington, D.C. airspace. A tentative TBS launch site has been found on the eastern shore of the bay (Figure 2). This site will complement the Kent Island site and together will serve as the Bay Node for CoURAGE.

3.3.4 Upwind Urban Node: Beltsville, Maryland and Washington, D.C. Sites

The Washington, D.C. metropolitan area is sometimes the upwind boundary condition for the city of Baltimore. This is especially true in summer high-pressure synoptic environments when heat and pollution are concerns. In these cases, the rural node may not provide a good representation of Baltimore’s upwind atmospheric conditions. Fortunately, extensive observational resources exist in the metropolitan region to the southwest of Baltimore.

The Beltsville, Maryland site (Figure 2), a partnership between HU and the MDE, is the fourth node of CoURAGE. It hosts many of the measurements (Table 2) found at the ARM core facility and in BSEC. Beltsville atmospheric composition instruments include MDE regulatory measurements of $PM_{2.5}$, ozone, NO, NO_2, SO_2, CO. Cloud and ABL atmospheric profiling instruments include an MDE radar wind profiler and a HU ceilometer, microwave radiometer, sodar, rawinsonde, and ozone sonde. A Doppler lidar is being added to the array. The Beltsville site includes a fully instrumented EC/SEBS and an array of radiation and precipitation measurements including a multi-filter rotating shadowband radiometer, a sun photometer, direct/diffuse incoming solar radiation, and, to be installed, a laser disdrometer. In addition to the Beltsville, Maryland measurements, Washington, D.C. hosts a NOAA/NIST Doppler lidar, a second HU Doppler lidar, and two additional ceilometers, in addition to the Dulles airport NWS rawinsonde site (IAD).

This node includes all the observations required for an ABL observatory and it is a well-instrumented site for cloud and radiation properties. Co-I DeCarlo will add an aerosol mass spectrometer and ancillary instrumentation to the Beltsville site for IOPs, making this location a complete atmospheric composition site during IOPs. This location is also a World Meteorological Organization-certified Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN) site capable of the most accurate upper air soundings (www.gruan.org).

3.3.5 Regional Collaborative Resources

Maryland Department of the Environment. The MDE operates many environmental measurements. Most relevant to this proposal is their radar wind profiler (RWP) network, which includes sites in eastern Maryland (Horn Point), the central location in Beltsville, and a far-western location (Piney Run), as noted in Figure 2. This RWP network provides a larger mesoscale context for our proposed tighter-domain, four-node wind profiling network composed of a mixture of RWPs and DLs. The MDE is also developing a statewide network of surface weather stations.

NOAA/NIST D.C. Doppler lidar. The NOAA Chemical Sciences Laboratory (NOAA CSL) in collaboration with NIST's Greenhouse Gas (GHG) Measurement Program has been making continuous Doppler lidar measurements in downtown Washington, D.C. since March 2022 to evaluate and improve atmospheric boundary-layer dynamics representation in atmospheric transport models.

University of Maryland, Baltimore County. Co-I B. Demoz operates a MPL at the UMBC campus Figure 3).

Morgan State University. Co-I R. Damoah operates a ceilometer on the MSU campus (Figure 3).

Unified Ceilometer Network. Collaborating investigators (https://ucn-portal.org/) are bringing together observations from a regional network of ceilometers. The group is working to provide routine retrievals of cloud and ABL depth data from the suite of observations. Many of the ceilometers are located in the mid-Atlantic region.

Aeronet. NASA Goddard Space Flight Center leads a network of sun photometers (https://aeronet.gsfc.nasa.gov/new_web/networks.html) that provide multiple observations of aerosol optical depth across the mid-Atlantic region.

Regional eddy covariance flux towers. National Ecological Observatory Network (NEON), NIST/PSU, United States Department of Agriculture-Long-Term Agroecosystem Research (USDA-LTAR) and others operate numerous eddy covariance flux towers in the mid-Atlantic region, encompassing forested, agricultural, and turf grass land covers. These flux towers often include four-component radiation data and ground heat flux or soil temperature profile data to complete the surface energy balance.

NIST GHG tower network. Baltimore-Washington is the location of NIST's Northeast Corridor urban GHG testbed (https://www.nist.gov/greenhouse-gas-measurements/urban-test-beds). The testbed operates 13 highly calibrated, tower-based CO_2/CH_4 mole fraction observations.

3.4 Pointing Modes/Special Operations

3.4.1 Radar Wind Profilers

The RWPs will be operated with mode switching such that they will collect vertical profile measurements when precipitating that can be used for convective vertical velocity (at times when the profiles of horizontal wind are not reliable).

3.4.2 Doppler Lidars

The DLs will be operated to obtain horizontal winds, turbulent winds in the vertical and horizontal directions, cloud information, and backscatter.

3.5 Value-Added Data Products

Most of the Core AMF1 value-added products (VAPs) listed in the ARM Translator Plan (Table 4; Giangrande et al. 2022) are critical for the goals of the CoURAGE campaign. In addition to these core VAPs, the following products are necessary to meet the stated science goals.

3.5.1 Clouds

CLDTYPE: Cloud Type Classification – For providing information on the cloud types observed over the AMF site to help in the interpretation of surface radiation and atmospheric state measurements.

COGS: Clouds Optically Gridded by Stereo product – For providing 4D reconstruction of cloud field (under appropriate conditions) for cloud life cycle and dynamics studies.

NDROP: Cloud Droplet Number Concentration – For use in study of aerosol cloud interactions and cloud radiative impacts.

SPHOTCOD: Cloud optical depth retrieved from multichannel sun photometer – Cloud optical depth, effective cloud droplet radius and liquid water path used for cloud process studies, cloud aerosol interactions, and cloud radiative impacts.

SatCorps satellite products – Geostationary satellite cloud macro- and microphysical property retrievals (https://cloudsway2.larc.nasa.gov).

3.5.2 Aerosols

MERGEDSMPSAPS: merged size distributions from the SMPS and APS – Provides a quality-controlled, continuous aerosol size distributions from 10 nm to 20 microns in diameter on a common particle diameter axis, which are needed for aerosol processes and aerosol-cloud interaction studies.

NEPHELOMETER: nephelometer – Produces quality-controlled measures of aerosol scattering and hygroscopic growth factor, which are needed to understand impacts of aerosol water-uptake on optical properties.

PSAP: particle soot absorption photometer – Provides quality-controlled measures of bulk aerosol absorption, which are needed to estimate aerosol direct radiative impacts.

SP2: single-particle soot photometer – Measures the black carbon mass of single aerosol particles from which a black carbon concentration is derived, which are needed to determine aerosol source apportionment and estimate aerosol direct radiative effects.

TDMA: tandem differential mobility analyzer – Provides quality-controlled measurements of aerosol dry-size distribution and size-resolved hygroscopic growth factors, which are needed to understand aerosol chemical composition impacts on sub-saturated water-uptake.

3.5.3 Atmospheric State

AERIPROF: AERI Profiles of Water Vapor and Temperature – Provides profiles of temperature and humidity that can be used to complement lower-time-resolution observations from radiosondes.

AEIRoe: AERI Thermodynamic Profile and Cloud Retrieval-Optimal Estimation – For providing boundary-layer profiles of temperature and humidity, liquid water path, and precipitable water vapor.

SONDEPARAM: convective parameters derived from radiosonde data – Provides integrated measures of environmental thermodynamic stability (e.g., convective available potential energy [CAPE], convective inhibition [CIN], lapse rate) that can be used in cloud process studies and classification of environmental conditions.

3.6 Tethered Balloon Deployment

3.6.1 TBS Payload

The ARM TBS will 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., temperature, pressure, relative humidity, 3D wind speed). In situ measurements of newly formed particles will be provided by Co-I Kuang via deployment of a guest-instrument TBS-ready condensation particle counter (CPC) modified to measure down to 1 nm in particle diameter that has been successfully deployed during prior TBS deployments to ARM sites (e.g., Southern Great Plains [SGP], Tracking Aerosol Convection Interactions Experiment [TRACER]). Co-I DeCarlo will deploy a miniature scanning electrical mobility spectrometer (mini-SEMS, Brechtel Manufacturing Inc.) as a guest-instrument to make high-time resolution measurements of the aerosol size distribution from 5 to 375 nm. Appropriate ARM support requests will accompany proposed guest deployments. Measurements of aerosol chemical composition will be accomplished via deployment of the size- and time-resolved aerosol collector (STAC) platform for in situ sample collection followed by offline analysis using Environmental Molecular Sciences Laboratory (EMSL) microscopy and mass spectrometry instrumentation.

The following ARM TBS instruments will be deployed: portable optical particle spectrometer (POPS; aerosol size distribution from 140 nm to 3 um), the TSI 3007 CPC (total aerosol number concentration larger than 10 nm), the microAeth® micro aethalometer (black carbon optical properties), IcePuck (ice particle nucleating potential), the DTS (distributed temperature sensor), cup anemometers, 3D sonic anemometer, and iMet RSB and XQ2 sensors (temperature, pressure, and relative humidity).

3.6.2 TBS Flight Plan

Proposed measurements will take place from a clearing at the TBS site on the eastern shore of Chesapeake Bay (Figure 2). There will be two two-week deployment of the TBS during each of two two-week IOPs, one in midsummer and midwinter. These deployments will observe seasonal variability in bay boundary-layer meteorology and vertically resolved aerosol microphysical properties in the complex bay-region atmosphere. Two-week deployments are needed to sample across multiple synoptic cycles within each season. We will attempt to coordinate the TBS flights with radiosonde launches at the urban and rural nodes. Launches will be made during daylight hours in clear air only, starting in the morning and extending into the afternoon as the boundary layer develops. Profiles and loiters will balance the need for capturing vertical transport (profiles) for in situ measurement versus collecting sufficient aerosol loading at a particular altitude (loiters) for offline analysis. For a given profiling launch, the TBS will be raised and lowered and reach a maximum altitude of 1500 m above ground level. A single launch (one cycle of raising and lowering the TBS), will take place every two hours. Loiter specifications will be determined by collection specific sampling protocols, estimated ambient aerosol loading and the day's weather conditions.

3.7 Collaborative Mobile Resources

The following mobile labs will be deployed in support of CoURAGE IOPs.

3.7.1 DeCarlo Atmospheric Composition Laboratory

Co-I DeCarlo mobile laboratory will be delivered to JHU in spring/summer of 2023 and will have onboard power via generator or power from line source and be instrumented with an aerosol mass spectrometer, proton transfer reaction time-of-flight mass spectrometer, additional aerosol size, distribution, and number measurements, and trace gas measurements of ozone, NO/NO_2, and CO, CO_2, and CH_4.

3.7.2 University of Albany ASRC Sprinter van Mobile Laboratory

The University at Albany Atmospheric Sciences Research Center (ASRC) Sprinter van mobile laboratory operated by Co-I J. Zhang may be available, pending proposals, to assist the AMF1 deployment in Baltimore. The ASRC mobile laboratory can be configured to monitor trace gases (i.e., O_3, NO_2, CO_2, HCHO, CH_4, etc.), VOCs collected in canisters and analyzed in the laboratory, particle chemical component mass concentration by HR-ToF-AMS, particle size distribution by SMPS, and meteorological parameters. The ASRC mobile laboratory can be deployed for either on-road or roadside measurements. With an appropriate electric power connection, it can also be parked to take measurements at one location for days to weeks.

4.0 Project Management and Execution

4.1 Science Team

The science team will be organized around the disciplinary legs of the investigation: 1) atmospheric boundary-layer dynamics and surface-atmosphere interactions; 2) aerosols and atmospheric composition; 3) clouds and radiation; and precipitation.

Project Leadership. PI Davis will lead the project and serve as the primary point of contact with DOE. The disciplinary leadership structure will be open based on community participation. Close collaboration with BSEC will be provided by Co-Is Zaitchik, Waugh, and DeCarlo. Co-Is Demoz, Dickerson, Gonzalez-Cruz, Jensen, Li, and Lombardo will help to fill out disciplinary leadership activities. Co-Is Li and Damoah are the MSU hosts of the ARM core facility. Co-Is Sakai and Chiao are contacts for the Beltsville observational node. Co-Is Kuang and DeCarlo are our leads for TBS operations.

Science team membership will be open. The initial membership includes the following members.

Atmospheric boundary-layer dynamics. Elie Bou-Zeid, PU.; Richard Damoah, MSU; Kenneth Davis, PSU; Belay Demoz, UMBC; Marco Giometto, Columbia University; Jorge Gonzalez-Cruz, UA; Katia Lamer, BNL; Natasha Miles, PSU; Ying Pan, PSU; Prathap Ramamurthy, City University of New York; Scott Richardson, PSU; Ricardo Sakai, HU; Benjamin Zaitchik, JHU.

Aerosols and atmospheric composition. Akua Asa-Awuku, UM; Christopher Boxe, HU; Peter DeCarlo, JHU; Russ Dickerson, U. M. Chongai Kuang, BNL; Wei Peng, PU; Darryn Waugh, JHU; Jie Zhang, UA.

Clouds, radiation, and precipitation. Sen Chiao, HU; Michael Jensen, BNL; Xiaowen Li, MSU; Kelly Lombardo, PSU; Dev Niyogi, University of Texas at Austin; John Peters, PSU.

4.2 Communications and Coordination

Overall communications and coordination will be managed via monthly science team meetings. These meetings will be open and will enable communications among science team members and between AMF1 staff and the science team. We will also maintain a Slack channel, a Google drive, and a CoURAGE email list.

Field operations. Most field operations will be managed by AMF1 staff and will not depend on weather conditions or time-dependent field coordination. The project aims to document all typical weather conditions that influence the urban atmospheric environment. Any additional measurements such as mobile facilities that choose to operate to complement CoURAGE will be asked to develop any required forecasting and operations independently, but to stay in close contact with PI Davis and the AMF1 staff. Scientific guidance for TBS field operations will be led by Kuang and DeCarlo in coordination with PI Davis and AMF1 staff.

Analyses. Annual hybrid science team meetings will be held in addition to monthly online coordination meetings. Side meetings in each of three disciplinary focus areas will also be initiated, with frequency dependent on investigator needs.

4.3 Data Management

CoURAGE complements the AMF1 observations with measurements from BSEC, the Beltsville observational node, and a variety of regional sensor systems. We will work with ARM and these individual data providers to create a merged data set, accessible through ARM, so that all elements of the four-node array are accessible to the scientific community with a minimum of complexity.

Each of the contributing elements of CoURAGE has its own data management approach, which we review.

4.3.1 Observatory Nodes

Baltimore Social-Environmental Collaborative. BSEC uses DOE's MSD-LIVE (The MultiSector Dynamics – Living, Intuitive, Value-adding, Environment;(https://msdlive.org/) system for data sharing and data archival. Data are open to public access, ideally within six months of data collection. We will work with ARM to determine how best to create a merged data resource from the AMF1 deployment. Dr. Yaxing Wei of Oak Ridge National Laboratory (ORNL) is the lead data scientist for BSEC.

Beltsville, Maryland. The Howard University Beltsville Campus (HUBC) and Howard University Interdisciplinary Research Facility (HUIRB) follow the NCAS-M II guidelines of data management (http://ncas-m.org/research/data-management/). Web page modules are being developed to present the current data within the NCAS-M II web page (http://ncas-m.org/~ncasm/beltsville/). HUBC and HUIRB data are freely available upon request. Persons requesting data might be asked to inform the appropriate scientist(s) in writing (or email) by indicating, in the metadata, how the data will be used, including any publication plans. Data requestors are asked to acknowledge the data source as a citation or in the acknowledgments. The redistribution of HUBC and HUIRB research data products are not permitted through third parties.

4.3.2 Mobile Laboratories

The **DeCarlo** and **ASRC mobile laboratories** will follow **BSEC** data policies.

Fixed location regional resources.

Maryland Department of the Environment. Data from the Department's RWP/radio acoustic sounding system (RASS) network is shared with the NOAA Earth System Research Laboratory's Meteorological Assimilation Data Ingest System (NOAA/ESRL/MADIS) as part of the Cooperative Agency Profiler network (CAP). Real-time and historical data can be accessed through the MADIS CAP Data Display or by subscribing to MADIS.

NOAA/NIST D.C. Doppler lidar. Wind and vertical velocity profiles and ABL depth data at 20-minute time resolution are available to the collaborators and the public typically within an hour of data being taken as monthly NetCDF files on the NOAA CSL website (https://csl.noaa.gov/groups/csl3/measurements/2021dcflux/calendar.php).

University of Maryland, Baltimore County. MPL are available from B. Demoz upon request. Data used for CoURAGE will be publicly archived.

Morgan State University. MSU ceilometer data (NetCDF) are available to the public on request. Data used for CoURAGE will be publicly archived.

Unified Ceilometer network. A data portal is under development. Routine data access is planned in the near future at (https://ucn-portal.org/).

Aeronet. Data are accessible online (https://aeronet.gsfc.nasa.gov/new_web/data.html). The data are open, but remain the domain of the PIs who maintain instruments. Data users are asked to consult with PIs when using their data.

Regional eddy covariance flux towers. The DOE AmeriFlux Management Project maintains an openly accessible database (https://ameriflux.lbl.gov/data/data-policy/) for eddy covariance flux towers. Most tower data are accessible via a CC-BY-4.0 license (open access).

NIST GHG tower network. Northeast Corridor GHG observations are publicly available and accessible at doi:10.18434/mds2-2491.

5.0 Science Analysis Plans

We describe an overview of analysis plans, then present the foundational tools for analyses that BSEC will provide. Finally we describe more specific analysis plans organized by research objective.

5.1 Analysis Plan Overview

Observational analyses. The four observational nodes will enable our team to observe contrasts in the regional atmospheric environment and explore the causes of these differences. Each node of the network contains observations of multiple elements of the interactive surface-ABL-cloud system (Figure 1) to be observed and quantified. The observational analyses will:

1. Quantify the long-term and episodic (e.g., extreme events) heterogeneity of the regional atmospheric environment.
2. Elicit hypotheses concerning the relative importance of regional surface heterogeneity in determining Baltimore's atmospheric environment.
3. Explore the processes likely to be responsible for these differences.

For example, we may observe persistent seasonal differences in ABL depth and cloud cover between sites (1). These differences may be highly correlated with differences in sensible and latent heat fluxes (2). These changes in surface fluxes may be driven by land use differences and available moisture, or by cloud cover gradients leading to differential incoming radiation (3).

Model-data syntheses. A major objective of our project, spanning all research objectives, is to test and improve the numerical models that are used to simulate the urban atmospheric environment. These models contain a quantitative expression of our hypotheses concerning the factors that govern the urban atmospheric environment. This data set will provide a uniquely rigorous testbed for our quantitative understanding of the urban atmospheric environment. We anticipate that these model-data comparisons will quantify the current ability of our modeling systems to simulate the urban atmosphere, identify areas where our current models and hypotheses have shortcomings, and provide guidance for model development.

These model-data evaluations will identify the processes essential for accurate simulations of urban climate in this complex coastal setting (ARM Decadal Vision Theme 4.3). The findings from this study should be applicable to many coastal cities.

5.2 BSEC Analytical Tools

In addition to the observations discussed above, BSEC will be maintaining numerical models that can support the analyses of the AMF1 data. These numerical tools will be accessible to both the BSEC science team and collaborators. These tools will include multiple configurations of the Weather Research and Forecasting Model (WRF), a variety of land-surface and hydrological models, and the Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM), the experimental, high-resolution configuration of DOE's Energy Exascale Earth System Model (E3SM).

The resources most relevant to this proposal are our WRF configurations and land-surface model development efforts. Our basic WRF configuration will have nested domains, with 9-3-1-km horizontal grid spacing and 900-300-100-km domains centered on the D.C./Baltimore region, with an option for an outer 27-km grid/2700-km domain. We have identified a baseline set of parameterizations and will likely implement reanalysis nudging at the coarsest domain. ABL turbulence will be parameterized. PSU will have research staff available to support modifications of this baseline for experimentation. Our modeling will be on DOE computing resources and accessible to any investigator with an account on the DOE supercomputers.

BSEC scientists plan to run experiments with the baseline model to improve performance, identify sources of bias, and quantify and reduce uncertainty. It is computationally feasible to run many annual-scale experiments. We will also support large-eddy simulations (WRF-LES) for studies of atmospheric turbulence, especially for improving representation of the urban surface layer. The University of Texas's Global Building Heights for Urban Studies (GLOBUS)-World Urban Database and Access Portal Tool (WUDAPT)-WRF model configuration provides a framework for urban canyon and vegetation feedback within the WRF-BEP (Building Effect Parameterization) modeling system. The BSEC urban EC/SEB flux towers will include multi-level, tower-based, surface-layer turbulence observations to test urban surface-layer representations in both WRF-mesoscale and WRF-LES.

BSEC research will also include evaluation of urban land-surface modeling and land-atmosphere flux simulations. EC/SEB flux towers, soil and vegetation measurements, and building data and measurements will be used to adapt existing land-surface models to the urban environment. We plan to combine land-surface modeling approaches available in the Noah land-surface model with multiparameterization options (Noah-MP), the urban canopy parameterizations (urban canopy model, UCM) and single-layer urban canopy model (SLUCM), and DOE's E3SM Land Model (ELM) to create a new generation of urban land-surface parameterizations that can be coupled to WRF. This site-based model development will be combined with testing and development of new urban land data inputs needed to inform the new land-surface models.

BSEC will also support either the Weather Research and Forecasting Model coupled with Chemistry (WRF-Chem) or Community Multiscale Air Quality Model (CMAQ) simulations of regional atmospheric composition. These simulations will begin with the baseline mesoscale WRF configuration noted above, with the addition of atmospheric chemistry. The atmospheric chemistry simulations can be updated as the regional atmospheric simulations are increasingly improved to represent the urban environment.

5.3 Analysis Enabled by the AMF1 Deployment

5.3.1 ABL Dynamics

The regional network of ABL observatories will create the most comprehensive collection of coastal-urban-rural ABL dynamics observations available to date. This network will enable new understanding of how these regionally heterogeneous Earth-atmosphere interactions combine to create the urban atmospheric environment of Baltimore.

Heterogeneous ABL development. BSEC investigators and other CoURAGE investigators will use the regional ABL observatory network to test their understanding of the processes that govern extreme heat and humidity in the city of Baltimore. The BSEC project has a strong focus on heat and moisture stress, and the potential to mitigate these stresses via urban land management. The regional ABL observatory network will provide a test bed that documents the heterogeneity of ABL state in the three primary environments surrounding the city, and the surface fluxes that drive these heterogeneous ABL states. We will first describe this heterogeneity, decomposing our findings as a function of season and time of day. We will also isolate extreme events to see if they diverge from seasonally averaged patterns. Second, we will evaluate the ability of the WRF modeling system to reproduce this regional ABL heterogeneity. The processes leading to these model-data differences will be diagnosed with the multi-state observational array provided by CoURAGE. Finally, we will attempt to minimize or eliminate model errors, guided by the process-based diagnoses. These analyses will explore new land-surface parameterization options including an exploration of the role of anthropogenic heat and water fluxes.

These findings will enable an unparalleled understanding of the dynamics of coastal urban ABL development. These results will inform the city of Baltimore regarding the degree to which urban land management alone is able to modify urban climate. The observational and numerical understanding of regional ABL dynamics will inform all the other CoURAGE science objectives.

Low-level jet. The regional observation network (Figure 2) will provide an unprecedented view of boundary-layer winds across the entire coastal region, in addition to thermodynamic soundings, especially during IOPs, across the entire domain. CoURAGE investigators plan to use these observations to:

1. Document the characteristics of the regional LLJ.
2. Evaluate their ability to simulate LLJ dynamics in this region.
3. Examine, with the atmospheric composition observatory network, the impact of the LLJ on regional air quality. Summer air pollution associated with the LLJ is a major health air quality concern.

Deployment of the AMF1 will provide information on the spatial variability of the formation of the LLJ and its interaction with coastal breeze and downslope burst of winds from the elevated locations to the west of Baltimore. The nature of regional LLJ events and evaluation of our ability to simulate these events will also clarify the impact of this LLJ on cloud and storm formation.

Bay breeze. Chesapeake Bay is likely to lead to complex internal boundary layers given its limited horizontal extent. This complex ABL environment is likely to alter atmospheric conditions in Baltimore, but quantitative understanding of the impact is challenging. CoURAGE investigators will use the bay ABL observations, including the bay-atmosphere flux measurements, the bay Doppler lidar, the coastal sodar from BSEC, and the inland observations in Baltimore to quantify the interactions between the bay and the urban atmosphere, including modifications to the bay breeze air as it moves onshore. The observed interactions will be simulated using the BSEC regional WRF-mesoscale modeling system. These data, especially when enhanced with TBS thermodynamics soundings over the bay during IOPs, will be used to assess the ability of the WRF surface layer and ABL parameterizations to accurately develop the marine layer, a known weakness in mesoscale numerical models. WRF-LES will be used for case studies in support of the mesoscale simulations. We expect this work to identify critical land-atmosphere and bay-atmosphere fluxes that must be parameterized well to capture the true bay breeze and bay ABL dynamics of this region (e.g., Yang et al. 2022). As with the LLJ study, understanding these regional mesoscale dynamics will support the urban climate, atmospheric composition, and cloud/precipitation studies.

The study of ABL heterogeneity across this regional observatory network and within Baltimore could be enhanced by deployment of BNL's Center for Multiscale Applied Sensing's vehicle-based mobile observatory. CMAS can obtain Doppler lidar and backscatter lidar data while in motion from one AMF site to the other, and from neighborhood to neighborhood within Baltimore.

5.3.2 Atmospheric Composition

Sustained, multi-site measurements of atmospheric composition across the region will quantify gradients of key atmospheric constituents across seasons, and their impact on climate-relevant properties such as CCN and new particle formation and growth.

Urban aerosol and trace gas emissions into regional airmasses. The Rural and Beltsville atmospheric composition and ABL observatories provide ideal locations for upwind characterization of airmasses that are transported to Baltimore under different synoptic flow conditions. The Rural site will provide background regional atmospheric composition characterization for air masses coming from the north and west, and the Ohio River valley region. The Beltsville site will provide a characterization of airmass outflow from the highly urbanized D.C. area. The one-year deployment will add to our understanding of how Baltimore's emissions add to the regional aerosol character and impact both atmospheric composition and aerosol particle populations, and how those impacts modify CCN and other climate-relevant properties. Aerosol composition, aerosol size distribution properties, and key trace gases will be compared between sites and used to test models. ABL measurements at these sites will provide context on atmospheric concentration measurements – that is, the degree to which changes in boundary-layer height and winds speeds impact the measured concentrations. During IOPs, the Bay and Beltsville sites will be instrumented by mobile laboratories (Co-Is DeCarlo and/or Zhang) to provide fully complemented atmospheric composition data at all neighboring sites. As a further check on atmospheric composition gradients between sites, mobile measurements of aerosol and trace gas concentrations may be conducted during IOPs (Co-Is DeCarlo and/or Zhang).

Processing and atmospheric chemistry of trace gases and aerosols. How atmospheric chemistry impacts aerosol composition and oxidation state will be tracked by proxy with measurements of ozone, NO, and NO_2. Oxidative chemistry is linked to formation of secondary products, and Ox (O_3+NO_2) has been shown to correlate strongly with secondary organic aerosol (SOA) formation, but the magnitude of SOA formation varies with location. These relationships will be tracked for the Baltimore region under different flow (rural versus D.C.) conditions, and provide in situ data for evaluating predictive models such as WRF-Chem.

CCN properties of aerosols. In addition to modifying atmospheric composition, atmospheric oxidation of trace gases and aerosols modifies climate-relevant properties of aerosols such as hygroscopicity, CCN formation, and their radiative properties. CCN and hygroscopicity measurements made at the Rural site (ARM AOS) will be complemented by CCN measurements made in Baltimore (BSEC instruments). Beltsville and Bay observatories will be similarly instrumented during IOPs. Co-Investigators Asa-Awuku and Zhang are focused on how urban emissions impact the regional CCN population. Of interest are how direct emissions of combustion-related particles impact CCN formation of aerosol populations, and how atmospheric processing changes hygroscopicity and CCN formation using single-parameter (κ) theory. These questions will use the proposed network of atmospheric composition data to identify which microphysical models of hygroscopicity best reproduce measured CCN populations. The findings of this work will inform CCN parameterizations in ESMs.

IOP – in situ TBS measurements of aerosol populations with height at the bay. Operations of the TBS adjacent to Chesapeake Bay provides an opportunity to measure vertical profiles of aerosol populations and aerosol bulk composition. TBS aerosol instrumentation using four CPCs with differing cut points and the POPS can be complemented (if payload allows) with a miniaturized scanning electrical mobility particle sizer (mSEMS, Brechtel Manufacturing) from Co-I DeCarlo. This low-power, small-footprint guest instrument would bridge the size range between the CPC units and the POPs with a 10-380-nm measurement range for scanning. The STAC, cascade impactors, and MicroAeth (AE-51) would provide size-resolved chemical information, with the STAC and AE-51 adding some information with height. This combination of instruments is ideal for characterizing the aerosol population within the bay breeze, and for identifying vertical variations in aerosol population with a focus on potential of new particle formation and growth. TBS operation during IOPs will provide seasonal context for understanding the vertical aerosol population structure across meteorological and seasonal changes.

The observational analyses will be complemented by an evaluation of the ability of the BSEC air quality modeling system to simulate these regional gradients in atmospheric composition. We anticipate that the improved understanding of regional ABL dynamics will improve simulation of Baltimore air quality, but that existing WRF-Chem or CMAQ parameterizations will have less success simulating regional aerosol characteristics. These limitations will provide motivation for additional study of the treatment of aerosols in these air quality modeling systems. We also anticipate that, in some cases, model-data comparisons will reveal shortcomings in regional pollutant emissions estimates and will provide motivation for additional work to refine emissions inventories.

5.3.3 Clouds and Radiation

Cloud cover variability and radiative properties. Satellite cloud cover products (https://cloudsway2.larc.nasa.gov) will be combined with the multi-site observations of cloud physical properties and surface radiation to create a testbed for simulation of clouds across all seasons, including day and night conditions. BSEC baseline WRF simulations will be tested against the spatially extensive cloud cover observation, as well as site-based observations of cloud properties and radiation, and combined with our growing understanding of regional ABL and atmospheric composition dynamics to create a state-of-the-science evaluation of our ability to simulate coastal urban cloud cover. The rich suite of observations available from this AMF deployment will provide the opportunity to evaluate how model resolution, physics, and dynamics may be improved to more realistically portray clouds and enable a wide range of more detailed investigations of cloud physical properties, their impacts on the rural environment, and top priorities for improving their representation in ESMs.

A critical outstanding question about convective clouds is what environmental factors regulate cloud width across the spectrum of cloud organizations spanning from shallow cumulus through cumulus congestus and isolated deep convection, to mesoscale convective systems. Cloud width regulates the dilution of updraft air parcels by the entrainment of air from the free troposphere, and cloud width consequently influences updraft buoyancy, intensity, cloud depth, and the transport properties of clouds. Wider clouds will tend to grow deep and become thunderstorms, whereas narrower clouds typically remain shallow. Hence, land surface and atmospheric factors that regulate cloud width also strongly influence the transition from shallow to deep convection. These factors potentially exhibit substantial spatial heterogeneity in the vicinity of urban regions, which has been shown to result in differing convective cloud behaviors in urban environments than in their adjacent regions (e.g., Theeuwes et al. 2019).

The proposed observational facilities will be capable of gathering key observations of a variety of atmospheric features and processes that potentially influence cloud width. For instance, we know there are certain atmospheric regimes wherein the size of ABL eddies regulates the width of the overlying shallow (and possibly deep) convection (e.g., Williams and Stanfill 2002, Mulholland et al. 2021). The size of ABL eddies is constrained by the depth of the ABL (e.g., Morrison et al. 2021), which will be continuously observed at all four regional observatories using DL. Cloud width is observable via radar, lidar, and satellite. Our observations of these features will address the critical question of whether spatial gradients in surface fluxes and ABL depth across regional surface gradients yield corresponding gradients in cloud behavior. For instance, are wider clouds found over urban areas? Are these more liable to produce precipitation than their narrower rural counterparts?

5.3.4 Precipitation

Precipitation mode evolution, precipitation intensity, and the distribution of total accumulation: Radar reflectivity from the comprehensive local network of NEXRAD and TDWR radars will be used to identify the initiation location of convective precipitating storms, their evolving intensity, and changing storm mode as they move across the domain. The quantitative spatial distribution of precipitation associated with these storms will be measured by a dense local network of rain gauges and compared to radar reflectivity patterns of the associated convective storms.

Regional atmospheric stability and wind shear associated with precipitation patterns: Tropospheric deep profiles of temperature, moisture, and wind will be done four times/day at the Baltimore ARM Core Facility, and from the Rural ARM site during IOPs, in additional to twice daily NWS rawinsondes launches from Wallops Island, Virginia (WAL) and coastal Sterling, Virginia (IAD). Data will be used to quantify the tropospheric deep stability characteristics (CAPE, CIN, lifting condensation level [LCL], level of free convection [LFC], convective instability) and vertical wind shear supporting the initiation, development, and evolution of convective precipitation.

Convective initiation and modification mechanisms. The coastal sodar, the Horn Point, Baltimore, and Beltsville RWPs, and Doppler lidars at all four ABL observatories will provide continuous measurements of lower atmospheric wind profiles, yielding a remarkable network available to quantify the convergence associated with local boundaries (bay breeze, rural-urban transition) and mesoscale flows (e.g., coastal LLJ) that may be responsible for the initiation and modification of precipitation-producing storms. The associated boundaries will also be identified and monitored with NEXRAD radial velocity data. Wind profilers will also measure the changing ABL vertical wind shear across the heterogeneous environment, a critical component governing the lifetime, intensity, and mode of precipitation storms. Additionally, profilers will measure the passage of and wind profile within cold pools from existing storms. The leading edge of a cold pool is typically several to 10s of km ahead of the storm precipitation and the cold pool is an important component of storm maintenance. The regional network of ceilometers and Doppler lidars will also measure cloud base height and, in combination with thermodynamic data, the LCL. Fluctuations in cloud base height will be used to diagnose the existence and passage of lower-tropospheric gravity waves (an important feature for the initiation and evolution of convection).

Impact of atmospheric composition. The onset of precipitation may be substantially affected by the concentration of atmospheric aerosols that serve as cloud condensation nuclei (e.g., Abbott and Cronin 2021). CCN-rich regions within the urban aerosol plume may produce shallow clouds that are slower to precipitate. Along these lines, shallow cumulus, CCN-poor regions within a maritime airmass may be quicker to produce precipitation and herald a more rapid transition into deep convection. The observing capabilities of the AMF will be capable of simultaneously observing aerosol concentration, clouds, and precipitation, which will allow us to characterize the potential relationship between aerosols and the shallow-to-deep transition of cumulus clouds.

IOP – Thermodynamic ABL heterogeneities. The regional network of thermodynamic profiles (AERI and sondes from Baltimore complemented during IOPs by sondes from the Rural site and TBS soundings over the bay, and MWRs at the Rural, Baltimore, Beltsville, and Bay sites) will measure lower-tropospheric thermal heterogeneities, specifically rural-urban and urban-coastal transition zones. Complementary to lower-tropospheric wind, lower-troposphere stability is also a critical component driving the evolution and intensity of precipitating convective storms. Further, upon encountering the bay breeze, storm response is determined by the buoyancy of the marine air, which can be calculated using these data. Horizontal and vertical thermal gradients associated with the UHI and coastal environment will be quantified to assess the role in regional precipitation intensity and spatial patterns. Horizontal gradients in lower-tropospheric moisture, in conjunction with wind data, will allow an assessment of regions of enhanced moisture convergence, important for convective storm initiation.

Extension to Earth systems modeling. Case-study simulations will be performed with the WRF to quantify the storm-scale physical processes (including processes not resolved by CoURAGE) associated with the observed evolution of precipitation. ABL and precipitation data gathered will be used to verify the atmospheric conditions and precipitation patterns produced by the model and identify its most prominent weaknesses. These model-data comparisons will guide the development of improved simulations of coastal urban precipitation under future climate scenarios.

6.0 Relevancy to the DOE Mission

The CoURAGE AMF deployment intersects with the ARM mission and Decadal Vision via our overall objective of improving our ability to understand the forces that determine urban climate and atmospheric composition, its response to climate change and human mitigation and adaptation efforts, and our ability to simulate these scenarios.

Specifically, our effort is directly responsive to the ARM mission to, “provide 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,” and the vision, “to provide a detailed and accurate description of the Earth atmosphere in diverse climate regimes to resolve the uncertainties in climate and Earth system models toward the development of sustainable solutions for the nation’s energy and environmental challenges.”

Our effort falls within the first and fourth themes of ARM’s Decadal Vision. Our deployment is intended to, “Provide comprehensive and impactful field measurements to support scientific advancement of atmospheric process understanding (theme 1).” Most specifically, we would contribute to Theme 1.5, “Enhancing the application of ARM observations to multi-scale analyses.” As noted in this theme discussion (ARM User Facility Decadal Vision, May 2021), “Looking ahead, ARM will seek to identify opportunities to deploy subsets of instruments, such as those that measure surface fluxes and boundary-layer height, to provide greater information about the representativeness of a main ARM site. This work would be aided by development of compact and modular observing systems that could be readily deployed with ARM observatories. One could also imagine the deployment of two or more ARM observatories in tandem to measure the evolution of atmospheric properties along a natural gradient…” In our case we will construct a network of four locations designed explicitly to examine the “representativeness” of any individual site by comparing observations across sites. Our request is an example of T1.5 and where this vision might lead ARM.

We also will contribute to Theme 4, “Accelerate and amplify the impact of ARM measurements on Earth system models by exploiting ARM and ESM frameworks to facilitate the application of ARM data to ESM development.” Most specifically, we will contribute to Theme 4.3, “Exploit model configurations and tools such as single-column models or regionally refined mesh to effectively link ARM data to ESMs,” by using our multiple site deployment to evaluate our high-resolution Earth-atmosphere modeling systems.

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