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Tracking Aerosol Convection Interactions ExpeRiment (TRACER) Science Plan

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Executive Summary

Convective clouds play an important role in the Earth's climate system as a driver of large-scale circulations and a primary mechanism for the transport of heat, moisture, aerosols, and momentum throughout the troposphere. Despite their climatic importance, multi-scale models continue to have persistent biases produced by insufficient representation of convective clouds. This is the result of an incomplete understanding of key processes such as convective initiation, updraft and downdraft dynamics, cloud and precipitation microphysics, and aerosol-convection interactions.

The Aerosol-Cloud-Precipitation-Climate Initiative, an international research group dedicated to advancing understanding of aerosol impacts on clouds relevant to climate, has identified the Houston, Texas region as an optimal location for targeted studies of aerosol-convection interactions within frequently developing isolated deep convection. Houston lies within a humid subtropical climate regime, where onshore flow and sea-breeze convection interact with a range of aerosol conditions associated with Houston's urban and industrial emissions. Pilot studies have suggested that convective clouds in this region are potentially significantly impacted by the varying aerosol conditions.

To increase our understanding of convective cloud life cycles and aerosol-convection interactions, the Tracking Aerosol Convection Interactions Experiment (TRACER) aims to collect a comprehensive data set focused on the evolution of convective clouds and the environment (including aerosol, cloud, thermodynamics, and lightning) in which the clouds initiate, grow, and decay. A unique component of TRACER is that a large number of individual, isolated convective cells will be tracked and measured in high spatial and temporal resolution for the purposes of:

(i) Characterizing and linking convective cloud kinematic and microphysical life cycles,

(ii) Quantifying environmental thermodynamic and kinematic controls on convective life cycle properties,

(iii) Isolating and quantifying the impacts of aerosol properties on convective cloud kinematic and microphysical evolution.

TRACER includes a one-year deployment of the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility's first ARM Mobile Facility (AMF1) and second-generation C-Band Scanning ARM Precipitation Radar (CSAPR2) aimed at collecting statistical data sets of cloud, precipitation, atmospheric state, and aerosol under varying aerosol loading and local circulation (sea breeze and urban heat island) conditions. A four-month intensive operational period (IOP) from June through September will include deployment of an ancillary site with aerosol, atmospheric state, and precipitation measurements at a location rarely impacted by Houston's anthropogenic emissions, which will be commonplace near the AMF1 site. Convective cell tracking by the CSAPR2 will provide high-resolution polarimetric and velocity observations under a range of environmental (including aerosol loading) conditions. High-frequency radiosonde launches will capture quickly evolving thermodynamic and kinematic conditions near convective cells, a requirement for isolating aerosol effects on clouds.

TRACER will additionally leverage a lightning mapping array, surface meteorological networks, and air pollution networks, and proposals will be entered to deploy additional mobile radar and radiosonde assets during the IOP. This unique combination of cloud, precipitation, lightning, aerosol, and atmospheric state measurements associated with tracked convective cells will ultimately improve our understanding of the convective cloud life cycle and its interaction with individual environmental factors such that improved, next-generation cumulus, microphysics, turbulence, and aerosol parameterizations can be designed.

Acronyms and Abbreviations

2D	two-dimensional
3D	three-dimensional
4D	four-dimensional
AAF	ARM Aerial Facility
ACE-ENA	Aerosol and Clouds Experiment in the Eastern North Atlantic
ACPC	Aerosol, Clouds, Precipitation, and Climate
ACSM	aerosol chemical speciation monitor
AERI	atmospheric emitted radiance interferometer
AERIoe	AERI Optimal Estimation Retrieval of Thermodynamic Profiles and Liquid Cloud Properties value-added product
AMF	ARM Mobile Facility
ANC	ancillary site
AOS	aerosol observing system
APS	aerodynamic particle sizer
ARM	Atmospheric Radiation Measurement
ASCII	American Standard Code for Information Interchange
BER	Office of Biological and Environmental Research
BL	boundary layer
CACTI	Cloud, Aerosol, and Complex Terrain Interactions
CAPE	convective available potential energy
CCN	cloud condensation nuclei, cloud condensation nuclei counter
CEIL	ceilometer
CLOWD	Clouds with Low Optical Water Depth
CN	condensation nuclei
CPC	condensation particle counter
CRM	cloud-resolving model
CSAPR	C-Band Scanning ARM Precipitation Radar
CWOP	Citizen Weather Observing Program
DCC	deep convective cloud
DEG CPC	diethylene glycol condensation particle counter
DOE	U.S. Department of Energy
DOI	Digital Object Identifier
DQPR	Data Quality Problem Reporting
ECOR	eddy correlation flux measurement system
GCM	global climate model
GOAmazon 2014/15	Observations and Modeling of the Green Ocean Amazon GOAmazon 2014/15
GOES	Geostationary Operational Environmental Satellite
HLMA	Houston-area Lightning Mapping Array

HS–RHI	Hemispherical Sky-Range–Height Indicator
INP	ice nucleating particle
IR	infrared
IOP	intensive operational period
KASACR	Ka-band Scanning ARM Cloud Radar
KAZR	Ka-Band ARM Zenith Pointing Radar
LDIS	laser disdrometer
LES	large-eddy simulation
LMA	Lightning Mapping Array
LT	local time
MC3E	Midlatitude Continental Convective Clouds Experiment
MERGESONDE	merged sounding value-added product
MET	surface meteorological instrumentation
MPL	micropulse lidar
MWR	microwave radiometer
NEXRAD	Next-Generation Weather Radar
NetCDF	Network Common Data Format
NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar-Orbiting Partnership
NWS	National Weather Service
PPI	plan position indicator
PR	higher-temporal-resolution precipitation
PRF	pulse repetition frequency
RACORO	Routine AAF CLOWD Optical Radiative Observations
RAIN	rain gauge
RH	relative humidity
RHI	range height indicator
RWP	radar wind profiler
SACR	Scanning ARM Cloud Radar
SCM	single-column model
SKYRAD	sky radiometers on stand for downwelling radiation
SMPS	scanning mobility particle sizer
SNR	signal-to-noise ratio
SONDE	radiosonde
SPARTICUS	Small Particles in Cirrus
TAMU	Texas A & M University
TAP/CLAP	tricolor or continuous light absorption photometer
TCEQ	Texas Commission on Environmental Quality
TRACER	Tracking Aerosol Convection Interactions Experiment
TSI	total sky imager

UHI	urban heat island effect
UHSAS	ultra-high-sensitivity aerosol spectrometer
VAP	value-added product
VARANAL	Large-Scale Forcing Data for SCM/CRM/LES from Constrained Variational Analysis value-added product
VCP	Volume Coverage Pattern
VDIS	video disdrometer
VHF	very high frequency
VIIRS	Visible Infrared Imaging Radiometer Suite
VISST	Visible Infrared Solar–Infrared Split Window Technique value-added product
XSACR	X-band Scanning ARM Cloud Radar

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1.0 Background

Convective clouds play a critical role in the Earth's climate system. They serve as a primary mechanism for the transfer of heat, moisture, and momentum through the troposphere, significantly impacting large- scale atmospheric circulation (e.g., Hartmann et al. 1984; Su et al. 2014; Sherwood et al. 2014). Convective clouds act as a sink of total water in the atmospheric column through precipitation, contribute to the atmospheric energy balance through diabatic heating effects, and alter the local environment to affect the probability of subsequent formation of clouds. Recent research has shown that realistic representation of convective processes is critical to constrain climate sensitivity in global climate models (GCMs; e.g., Sanderson et al. 2010; Zhao et al. 2016). Furthermore, predictions of increasing deep convective extreme precipitation and severe weather in a warming climate suggest significant vulnerabilities of life and property, highlighting the critical importance of improving deep convection representation in numerical weather prediction models for resiliency planning (e.g., Trapp et al 2009; Diffenbaugh et al 2013; Sillmann et al 2013; Seely and Romps 2015). A key component of improving model representation of convective clouds is better quantification and parameterization of updraft microphysics and dynamics including their interactions with the surrounding environment and storm organization (Bony et al. 2015; Hagos and Houze 2016).

Current understanding of fundamental interactive processes between aerosols, cloud dynamics, and microphysics is uncertain. This is partly the result of a lack of comprehensive and robust observations that are required to confidently isolate and quantify aerosol effects over a range of thermodynamic and kinematic environments. Theoretical and modeling studies showed aerosols could have a strong dynamic feedback to convection in warm and humid environments through enhancing ice-related processes (Rosenfeld et al. 2008) and condensational growth (Fan et al. 2018). A few observation-based studies have suggested an influence of aerosols on convective cloud and precipitation properties (e.g., Andreae et al. 2004; May et al. 2011; Braga et al. 2017; Seela et al. 2017; Fan et al. 2018). However, robust observational quantification of an aerosol effect on convective clouds isolated from other factors often remains uncertain (e.g., Varble 2018). In part, the uncertainty in aerosol-convection interactions is due to an incomplete understanding of the underlying convective dynamical and microphysical processes.

In order to methodically advance observation-based understanding of fundamental convective cloud processes and aerosol impacts on these processes, the Tracking Aerosol Convection interactions ExpeRiment (TRACER) will focus on the collection of measurements of the evolution of detailed convective cloud properties and the environment, including thermodynamic and aerosol properties, in which the convection initiates, propagates, and decays. The campaign currently includes the deployment of the first ARM Mobile Facility (AMF1) with the second-generation C-Band ARM Scanning Precipitation Radar (CSAPR2) and an ancillary site (ANC) with meteorological and aerosol measurements near Houston, Texas, USA. The deployment benefits from an existing network of air quality monitoring stations that include observations of surface meteorological parameters, trace gas, and particulate matter, as well as coverage by a Lightning Mapping Array (LMA). We also expect additional interagency and international contributions to the measurement activities related to the TRACER campaign. The Houston region offers a unique environment where isolated convective systems are common and experience a spectrum of aerosol conditions, from urban and industrial pollution sources to significantly lower background aerosol conditions southwest of the city. The TRACER deployment will provide measurements that are intended to be used hand in hand with high-resolution and large-scale models to improve simulation of the life cycle of isolated convective cells, including effects of interactive aerosol, microphysical, and dynamical processes on observable cloud, precipitation, and electrification signatures.

2.0 Scientific Objectives

TRACER will provide detailed, targeted observations of clouds, with a focus on convective clouds, using the full complement of AMF1 instrumentation, cell tracking with the CSAPR2, and complementary aerosol, atmospheric state, and lightning observations from the ARM facility and existing operational networks. The integrated TRACER data set is designed to improve understanding and model representation of the life cycle of convective clouds, including how it is influenced by thermodynamic and kinematic profiles, aerosol properties, and urban and coastal geography.

The main objective of the TRACER campaign is to provide observations of convective clouds in the Houston region of high temporal and spatial resolution, over a broad range of environmental and aerosol regimes. These observations are needed to better constrain high-resolution numerical simulations, advance fundamental process-level understanding of updraft kinematics and microphysics (including aerosol and lightning signatures), and improve the representation of deep convection in multi-scale models.

Specifically, TRACER aims to provide the following field data:

1. Routine, high-resolution, four-dimensional (4D) observations of isolated convective cells spanning their full life cycle over the relatively wide range of environmental thermodynamic and aerosol conditions found in the Houston region.
2. Quality-controlled, 4D retrievals of polarimetric radar variables and rain properties (rain rate, raindrop size distribution parameters) spanning observed life cycles of isolated convective cells.
3. Boundary-layer thermodynamic evolution, 4D low-level horizontal wind divergence (in precipitation region), and convective cell kinematic evolution uniquely colocated with polarimetric and lightning mapping array measurements.
4. A full annual cycle of aerosol, cloud, and radiative observations in a variably polluted, subtropical, humid coastal environment that experiences a wide range of meteorological influences.
5. A measure of the temporal and spatial variability in cloud and precipitation properties, meteorology, particulate matter and trace gases, and lightning in the Houston metropolitan region.

2.1 Science Questions

2.1.1 Convective Cloud Life Cycle

The Byers and Braham (1949) deep convective cell model shows that the cloud life cycle consists of updrafts that grow precipitation particles followed by heavy precipitation that drives downdrafts and leads to cloud dissipation. However, complicated microphysical and dynamical processes strongly control the details of convective life cycle components including updrafts, downdrafts, and cold pool circulations, hydrometeor type and size distribution, anvil properties, and probabilities of severe weather and further deep convective initiation and growth. For example, aerosol warm cloud-nucleating and ice-nucleating properties may influence hydrometeor size distributions, but so do updraft properties, complicated mixed- phase interactions, and mixing with cooler, drier, environmental air. Downdrafts produced by sedimentation, latent cooling, and hydrometeor loading can promote further cloud growth by producing cold pools that interact with environmental vertical wind shear to lift low-level air (e.g., Takeda 1971; Rotunno et al. 1988; Weismann and Rotunno 2004; Stensrud et al. 2005; Bryan and Parker 2010), but they also convectively stabilize the environment, which acts to suppress further convective cloud growth. Synergy between these processes is complex.

Convective updraft and downdraft dynamics have a significant control on vertical water, heat, momentum, and aerosol vertical fluxes within the convective cloud system. Despite their importance, they remain poorly understood, difficult to measure, and a cause of great uncertainty in microphysics and cumulus parameterizations. In cloud-resolving and mesoscale models, modern model microphysics schemes produce widely divergent results (e.g., Zhu et al. 2012; Fan et al. 2017) that are not remedied by simply increasing model spatial resolution because microphysical processes that feedback to dynamics remain poorly constrained (e.g., Varble et al. 2014a). Some cumulus parameterizations still exclude downdrafts, and many only calculate mass flux, in part because of the paucity of observational constraints. Only a handful of cumulus parameterization schemes have included microphysics in updrafts, to varying degrees of complexity (Sud and Walker 1999; Zhang et al. 2005; Song and Zhang 2011; Elsaesser et al. 2017). Limited studies indicate that updraft microphysics has important effects on cloud water budget and cloud radiative forcing in climate models (Song et al. 2012; Storer et al. 2015). Improved representation of convective clouds in models necessitates improved quantification of updraft and downdraft thermodynamic and microphysical characteristics and their relationships with both the surrounding environment and storm organization (Bony et al. 2015; Hagos and Houze 2016).

Key Questions

- What are the characteristic sizes of convective updraft and precipitation cores?
- How do the width and depth of updrafts and precipitation that define convective cells covary?
- Where and when are cloud/rain/snow/graupel/hail particles generated in convective cells, and how do they relate to updraft evolution?
- How are these particles transported and transformed in the cloud and how do they impact updraft, downdraft, and cold-pool properties?
- How well are these processes and properties represented in a hierarchy of models?

2.1.2 Meteorological Controls on Convective Life Cycle

Convective life cycle, from initiation to maturity and dissipation, is driven by a combination of dynamical, thermodynamical, microphysical, and radiative processes that are strongly coupled and variable in time, space, and region. Convective draft characteristics are controlled by pressure perturbation fields caused by draft buoyancy and interactions with environmental conditions. These interactions depend on draft size and speed in addition to environmental relative humidity and vertical wind shear. These characteristics then have an impact on convective mass flux, hydrometeor growth, evaporation and sedimentation, cold-pool properties (and subsequent convective initiation), and anvil characteristics with implications for the spatial redistribution of heat, moisture, momentum, and aerosols. Cumulus parameterization in large-scale models often assume that individual convective clouds are unorganized and interact through their shared environment. Therefore, TRACER's focus on isolated convective clouds will provide a clean setting for testing and improving cumulus parameterizations, which are necessary for reducing persistent biases in modeled deep convection (Hagos and Houze 2016).

The city of Houston is located approximately 75 km from the Gulf of Mexico coastline. A number of studies have shown that precipitation and convection in coastal regions are strongly modulated by coastlines (Pielke, 1974; Holland and Keenan 1980; Simpson and Brittner 1980; Baker et al. 2001). Recent studies have even suggested that clouds and rainfall in coastal regions demonstrate less dependence on large-scale meteorological conditions than purely oceanic or continental regions (Bergemann and Jakob 2016; Birch et al. 2016). This difference is due to the influence of mesoscale land-sea breeze circulations that drive local convergence zones, convective initiation, and convective organization (Haurwitz 1947; Rotunno 1983). The land-sea breeze circulation over the Houston region is complicated by interactions between the Galveston Bay breeze and the Gulf of Mexico sea breeze (Kocen 2013). In addition, the extensive Houston urban land surface could modify bay and sea-breeze circulations significantly (Chen et al. 2011).

In addition to land-sea breeze circulations, the sprawling Houston urban landscape may significantly affect convective cloud and precipitation properties through alteration of surface fluxes, surface roughness, and production of aerosols (e.g., Rozoff et al. 2003; Shepherd 2005; van den Heever and Cotton 2007). Convective forcing may strengthen through enhanced surface convergence due to the increased surface roughness of the urban landscape over surrounding rural areas (e.g., Changnon et al. 1981; Bornstein and Lin 2000; Thielen et al. 2000). Additionally, surface heating due to the Urban Heat Island effect (UHI; combination of both relative increase of heat capacity of surfaces and anthropogenic heating) can locally alter convective instability and inhibition while driving low-level circulations that affect convective cloud growth (e.g., Shepherd et al. 2002; Shepherd and Burian 2003). Multiple studies have used long-term operational weather radar observations to investigate urban impacts on convective initiation (Haberlie et al. 2015; Ashley et al. 2012), rainfall (Ganeshan et al. 2013), lifetime (Ashley et al. 2012), and other characteristics of convective storms (Kingfield 2018). For coastal cities, interaction between the UHI and sea-breeze circulations has been shown to result in an increase in the frequency and intensity of positive rainfall anomalies (Ganeshan et al. 2013).

Variability of bay and sea breeze intensity, depth, and propagation combined with the Houston UHI effect and variable background meteorological conditions could cause significant spread in deep convective life cycle properties. This complicates isolation and quantification of aerosol-deep convective cloud (DCC) interactions over this region, like many others around the world, but motivates the necessity of a dedicated field campaign such as TRACER. As highlighted in Varble (2018), aerosol properties can significantly correlate with convective meteorological parameters. Therefore, a primary objective of TRACER is to measure the covariability of evolving aerosol and meteorological properties while connecting them to evolving boundary-layer thermodynamic conditions, mesoscale circulations, and convective cloud characteristics. By first characterizing convective cell kinematic and microphysical properties and relationships, the dependency of these properties and relationships on first-order meteorological factors will then be quantified with the following questions.

Key Questions

- How do the properties of the pre-convective boundary layer and free troposphere control the initiation, location, and intensity of convective cells?
- How do environmental thermodynamic conditions and wind shear profiles influence the evolution of convective core size, updraft/downdraft size/strength, and cold-pool properties?
- How can observations of such meteorological controls on convection be used to improve representation of convection in large-scale models?
- What impact does the Houston urban land have on local circulations, deep convective initiation location/timing, and deep convective life cycle properties?
- How do the Galveston Bay breeze and Gulf of Mexico sea breeze properties influence deep convective initiation location/timing and properties of evolving deep convective cells?
- How do precipitation, land-sea breeze circulations (including both bay breeze and gulf sea breeze and gulf breeze), and UHI circulations modulate aerosol variability and aerosol-cloud-precipitation interactions?

2.1.3 Aerosol-Deep Convective Interactions

More than a decade ago, based on observations of Amazonian deep convection, Andreae et al. (2004) hypothesized that the suppression of warm rain as a result of reduced droplet size in polluted conditions could lead to the dynamical invigoration of DCCs due to enhanced lofting and freezing of cloud water. This was followed by a modeling study of the impacts of aerosols on deep convection over Florida by van den Heever et al. (2006) that demonstrated that enhanced aerosol loading led to consistently stronger updrafts. The underlying theoretical basis was presented in Rosenfeld et al. (2008), showing that this “cold-phase invigoration” could be significant for warm cloud-base DCCs. These studies stimulated many follow-on studies, showing that aerosol-DCC interactions are modulated by many factors such as wind shear (e.g., Fan et al. 2009, 2012; Khain 2009; Lebo et al. 2012), relative humidity (RH; e.g., Fan et al. 2007b; Khain et al. 2009), convective available potential energy (CAPE; e.g., Storer et al. 2010; Storer and van den Heever 2013), and cloud-scale circulations such as gust fronts (e.g., Khain et al. 2005; Lee et al. 2008). In real-case simulations, Fan et al. (2012) found the “cold-phase invigoration” is significant for mid-latitude DCCs with warm cloud bases and relatively weak wind shear. More recently, a number of studies have indicated that “condensational invigoration” or “warm-phase invigoration”, the enhancement of convection through condensational heating, also appears to play a role in enhancing both shallow cumuli (Seiki and Nakajima 2014; Saleeby et al. 2015) and deeper tropical convection (Lebo and Seinfeld 2011; Sheffield et al. 2015). For very warm and humid tropical DCCs, where warm-phase processes dominate, a recent study employing observations and modeling simulations from the Observations and Modeling of the Green Ocean Amazon (GOAmazon 2014/15; Martin et al. 2016) campaign suggested that small aerosols from an urban pollution plume can enhance convection and precipitation through increased condensational heating due to the nucleation of numerous small particles in a highly supersaturated cloud (Fan et al. 2018; referred to as “warm-phase invigoration”).

The warm and humid conditions of the Houston area are conducive to potentially significant “warm-phase invigoration” revealed in Fan et al. (2018). Past modeling studies showed the significant impacts of aerosol composition on the summertime thunderstorms in the Houston area (Fan et al. 2007a) and convective invigoration by aerosols through enhanced condensation (Fan et al. 2007b). Recent high- resolution retrievals from the National Polar-Orbiting Partnership (NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) satellite observations (Rosenfeld et al. 2016) reveal that contrasting aerosol conditions occur with a magnitude at least as large as the variability seen during the GOAmazon campaign, when comparing the Houston air pollution plume region to nearby areas. A dedicated field campaign near Houston will enable the examination of aerosol variability, convective cloud properties, and the corresponding susceptibility of DCCs to aerosol variability to gain better understanding of whether deep convection around Houston is significantly impacted by changes in aerosol conditions.

Aerosol-DCC interaction is rarely represented in regional and global climate models due to the lack of both observational quantification and modeling capability. Even in models that do include aerosol-deep convection interaction (Song and Zhang 2011; Lim et al. 2014), there is large uncertainty in accounting for a specific interaction mechanism. As described above, both "cold-phase invigoration" and "warm- phase invigoration" involve cloud microphysical processes in convective updrafts. TRACER observations of cloud dynamic, thermodynamic, and microphysical properties are not only critical to better understanding the mechanisms in aerosol-DCC interaction, but also vital to convective microphysics parameterization accounting for the role of aerosols in cloud droplet and ice particle formation in updrafts. Observations of cloud hydrometeor lofting and particle sedimentation under different aerosol conditions will provide useful constraints to the parameterization of microphysical processes in convective updrafts including autoconversion of cloud water/ice to rain/snow, accretion of cloud water by rain, accretion of cloud water, cloud ice, and rain by snow, homogeneous and heterogeneous freezing of rain to form snow, Bergeron-Findeisen process, fallout of rain and snow, condensation/deposition, self-collection of rain drops, and self-aggregation of snow.

Key Questions

How do aerosols and convective cloud properties vary across the Houston region and how do aerosols covary with meteorological conditions?

- Which aerosol sources in the urban, industrial, and maritime Houston environment facilitate ice nucleation?
- Which physical processes and properties within deep convective systems are most influenced by variation in aerosol conditions (e.g., warm-phase or cold-phase processes)?
- What are the necessary spatial-temporal constraints required to document and understand the dynamics in deep convective clouds and interactions of aerosol-microphysics?
- How are aerosol-deep convection interactions via cloud microphysical processes best represented in global and regional climate models?
- Is there evidence that aerosols enhance lightning?
- How do aerosols affect the height of and type (raindrops or ice particles) of precipitation initiation?

3.0 Measurement Strategies

In order to advance our understanding of convective cloud life cycle and how it is influenced by the environmental state, including local dynamical, thermodynamic and aerosol impacts, we must quantifiably observe the covariability of cloud, precipitation, atmospheric state, and aerosol properties over a significant number of convective events. The ARM facility provides state-of-the-science measurement capabilities across this spectrum with particular strengths in the routine, long-term measurement of detailed air mass aerosol characteristics across the aerosol particle size spectrum, research-grade polarimetric radar capabilities (recently upgraded with the CSAPR2), and robust measurements of the accompanying cloud, radiation, and atmospheric state. The unique combination of this suite of measurements, with existing operational networks and high-resolution modeling, will result in an opportunity to advance our understanding of deep convective cloud life cycle and how its characteristics are influenced by aerosol variability.

More specifically, a leading reason for the lack of fundamental understanding of coupled microphysical and dynamical processes in convective updrafts is scarce observational data from the insides of deep convective cores around the world (e.g., Fridlind et al. 2015 and references therein). Armored aircraft have been used to transit convective cores over land (e.g., Musil et al. 1986), but such measurements are rare and expensive. While in situ measurements along pencil-thin aircraft transits remain the only means of accurately retrieving hydrometeor size distributions and the details of hydrometeor shape that reveal process history, these measurements lack context and, therefore, remote sensing is needed to characterize rapidly evolving 3D structures within convective clouds.

Since first used meteorologically in the 1950s, radar has been the centerpiece for cloud and precipitation observations (e.g., Byers and Braham 1949). Today, we enjoy a golden age for radar observations, propelled by continuous technological innovations that have led to the development of sophisticated radar systems that offer amplitude (radar reflectivity), phase (Doppler velocity), and polarization (e.g., differential reflectivity, specific differential phase) measurements (Ryzhkov and Zrnić 2019; Zrnić and Ryzhkov 1999). Long-term deployment of research-grade dual-polarimetric radars opened new avenues for the study of internal storm microphysics, including hydrometeor identification (e.g., Keenan et al. 1998). Within rain, polarimetric observations are allowing improved retrieval of rain rate and colocated retrieval of raindrop size distribution properties (e.g., Bringi and Chandrasekar 2001); under specific conditions, polarimetric retrievals of ice properties are also beginning to emerge. For less than a decade now, scanning operational weather radars in the United States have been upgraded to dual polarimetric capabilities (National Oceanic and Atmospheric Administration [NOAA] 2017). The ARM facility has integrated all these concepts and led to the design of heterogeneous (multi-frequency) networks of radars with the capability for adaptive sampling strategies that provide a holistic view of cloud systems as coherent 4D entities with large dynamic range, rather than 2D or 3D projections of parts of their lifetime, thus overcoming artificial separations that do not exist in nature (Jensen et al. 2016; North et al. 2017).

Polarimetric radar systems can be especially valuable for the study of convective updraft physics (e.g., Loney et al. 2002; Snyder et al. 2015). For instance, comparison of reflectivity and phase-shift differentials between horizontal and vertical radar polarizations yields differential reflectivity (Zdr) and specific differential phase (Kdp), which are related to the presence of horizontally aligned oblate or prolate hydrometeors when positive (Bringi and Chandrasekar 2001). Vertically elongated columns of positive Zdr and Kdp that extend above the environmental melting level (so-called Zdr and Kdp columns) have been generally attributed to the presence of supercooled liquid associated with a deep convective updraft that is not otherwise identifiable from reflectivity alone (Bringi et al. 1996; Hubbert et al. 1998; Loney et al. 2002; Kumjian et al. 2014a). Recent studies suggest a strong connection between Kdp and Zdr columns and other metrics of deep convective activity such as overshooting tops

(Homeyer and Kumjian 2015), lighting flash rate, and updraft mass flux (van Lier-Walqui et al. 2016). Observations also show differences in Kdp versus Zdr column morphology (Zrnić et al. 2001; Loney et al. 2002; Kumjian and Ryzhkov 2008), which have been attributed to differing sensitivities to hydrometeor size distribution and phase characteristics (e.g., Kumjian et al. 2014b; Snyder et al. 2017). Although precise attribution of specific morphological features at various wavelengths remains a challenge, foundational analyses can be expected to emerge that will allow the sort of fundamental advances that have long been used from the first generation of weather radars, such as basic division of storm coverage into convective (core-containing) and stratiform areas (e.g., Steiner et al. 1995). In parallel, the use of single-, dual-, or multi- Doppler radar analyses and the use of profiling radar measurements have led to significant advancements in our understanding of convective cloud dynamics, their relationship to environmental factors, and their impact on storm microphysics (Bruning et al. 2007; May et al. 1999; Williams et al. 2012; Giangrande et al. 2013; Kumar et al. 2015; Nicol et al., 2015; North et al. 2017).

The Aerosol-Cloud-Precipitation-Climate (ACPC) Initiative (http://acpcinitiative.org/), an international research group dedicated to advancing understanding of aerosol impacts on clouds relevant to climate, has identified the Houston region as one optimal location for targeted studies of aerosol, convective cloud, and precipitation processes (Quaas et al. 2015). The Houston region is warm and humid in the summer, and commonly experiences onshore flow and sea breeze-forced convection, which interacts with a range of aerosol conditions associated with Houston's urban and industrial emissions.

The TRACER siting strategy is to deploy the AMF1, with its full suite of cloud, aerosol, precipitation, and atmospheric state measurements in a region that experiences the full diversity of aerosol properties from Houston/Galveston area urban, industry, refinery, and marine sources. An ancillary site (ANC) will be deployed in a region that is expected to experience conditions representative of the continental background atmospheric state for this region. The CSAPR2 will then be deployed between these two sites such that it is located approximately 30 km away from the AMF1 site (for ideal sampling of the convective core over the site). The distance from the CSAPR2 to ANC will ideally also be in the 20– 40 km range but could be further to accommodate more pristine observations at the ANC site. Based on these needs, we propose the use of the La Porte, Texas airport as an appropriate site for the AMF1 (See Figure 1).

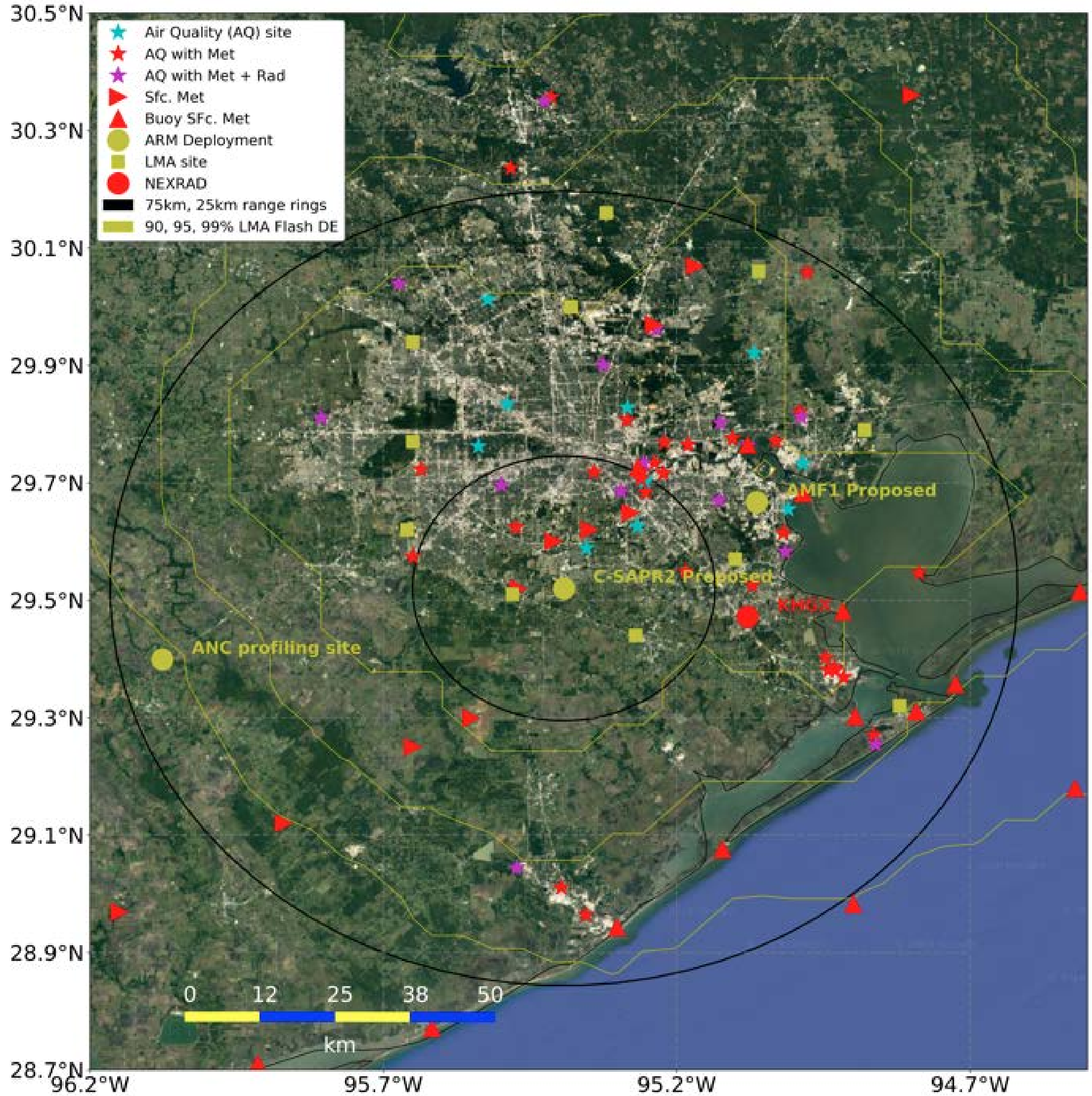

Figure 1. Map showing proposed (approximate) deployment areas for the AMF1 (near La Porte, Texas airport), CSAPR2 (near Manvel-Criox, Texas) with 25-km- and 75-km-range rings and an Ancillary site (ANC). Stars indicate the location of Texas Commission on Environmental Quality (TCEQ) monitoring sites with colors representing the instrumentation at each site. Triangles represent National Weather Service (NWS) and buoy surface meteorological measurements. The Houston-area Lightning Mapping array stations are indicated by the yellow squares with the yellow contours representing the flash detection efficiencies of 90, 95, and 99%.

3.1 Timing and Duration

TRACER is scheduled for the period from 15 April, 2021 through 15 April, 2022 with an intensive operational period (IOP) from 1 June through 30 September, 2021. The aim of the proposed deployment is to collect a full year of joint observations of aerosol, cloud, precipitation, atmospheric state, radiation, and lightning in a subtropical humid climate regime that experiences influences from the urban and coastal environment. A particular focus is the influence of aerosols on convection. The Houston metropolitan region experiences convective initiation on a regular basis throughout the year. A convective cell tracking algorithm (Picel et al. 2018) was used to develop cell tracks over four years of Next-Generation Weather Radar (NEXRAD; KHGX) data in order to provide a climatology of cell occurrence, initiation, and dissipation times. Figure 2 includes (left) the percentage of days each month when isolated cells were present and (right) the total number of isolated cells identified during each month. This climatological analysis from the Houston/Galveston area shows that convective initiation occurs in this area on 40–55 percent of the days each month of the year (Figure 2, left). However, the total number of convective events peaks strongly during the months of June through September (Figure 2, right).

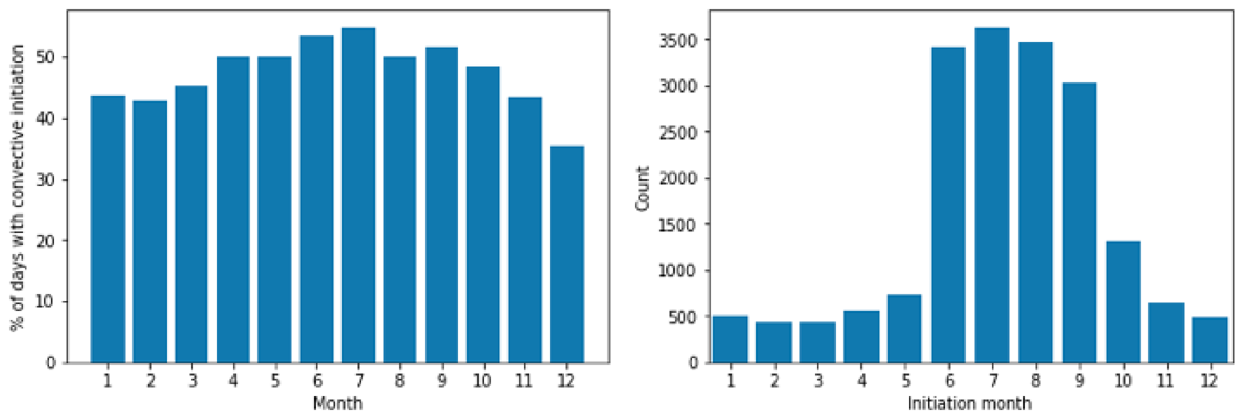

Figure 2. Monthly statistics based on the analysis of four years of observations from the Houston/Galveston NEXRAD radar (KHGX) of (left; Figure 11 from Fridlind et al. 2019) the average percentage of days per month with observed convective cells and (right; Figure 10 from Fridlind et al. 2019) the total number of convective cells detected each month over the four-year analysis period.

3.2 Intensive Operational Period Plan

The IOP will occur between 1 June and 30 September, 2021 and will involve the forecasting of daily convective conditions that will drive the operational mode of CSAPR2 scanning and the frequency of radiosonde launches at the AMF1 and ANC sites. Forecasts of convective conditions and nominal aerosol conditions will be made by the science team and collaborators. Logistically, this forecasting activity will follow successful methods used during the previous ARM Aerial Facility (AAF) campaigns, Routine AAF Clouds with Low Optical Water Depth (CLOWD) Optical Radiative Observations (RACORO; Vogelmann et al. 2012) and Small Particles in Cirrus (SPARTICUS; Mace et al. 2009), where forecasting discussions and decisions were done remotely and responsibilities were rotated among participating scientists on two-week shifts.

During the IOP, radiosondes will be launched from the AMF1 and ANC sites every 1.5 hours on convective days beginning at noon local time or just before (dependent on forecast conditions) in order to best capture the rapid daytime evolution of atmospheric thermodynamic conditions during times when deep convection is forming and evolving. On these convective days, the CSAPR2 will employ cell- tracking capabilities with detailed observation of the polarimetric radar signatures of convective cells, from initiation (or as close as possible) through to the decay of the convective cell when possible. A balance between rapid scan rates and polarimetric data quality will be determined in consultation with the

ARM radar engineering and operations team. Likewise, there are many decisions to be considered in the application of cell tracking. On a given day during the IOP period, we expect to commonly track and sample multiple cells passing over or nearby the AMF1 and ANC sites.

A key part of the TRACER plan is to provide aerosol observations suitable for better constraining environmental conditions for models and observational analysis than was possible for any study of this region outside of aircraft campaign periods. Routine air-quality measurements, including concentrations of PM2.5 (aerosols with diameters of < 2.5 micrometers) and PM10 (diameters of < 10 micrometers), do exist throughout the area. However, aerosol parameters required to address microphysical properties such as cloud condensation nuclei (CCN), ice nucleation particle (INP) concentration, and total submicron condensation nuclei (CN), are not included. Unfortunately, TRACER will not be able to provide aerosol measurements suitable to constrain CN, CCN, and INP over the entire Houston region, but two sites will be specifically targeted to sample relatively cleaner conditions to the southwest (ANC) and relatively more polluted conditions to the northeast (AMF1). It is intended that these will be combined with modeling efforts to directly constrain cloud-active aerosol trends at two differing locations, continuously in time. We note that the isolated cells that form under onshore flow conditions occur when the boundary layer is growing during the daytime and can be considered relatively well mixed such that surface aerosol may be relatively more representative of cloud-base conditions than during the morning or night. As convective clouds get deeper, free tropospheric CCN can play a much larger role influencing cloud properties (Lebo 2014). While remote-sensing observations (e.g., micropulse lidar) can provide some constraints on the heterogeneity of free tropospheric aerosol, the detailed CCN measurements needed require aircraft or specialized sounding observations. Recognizing this issue, we will target initial deep convective cells before the free tropospheric environment becomes heavily modified by the convection.

3.3 First ARM Mobile Facility (AMF1)

The AMF1 will be deployed for the entire campaign (15 April, 2021–15 April, 2022) near La Porte, Texas. In order to address the science goals of the campaign, AMF1 observations will be used to quantify the thermodynamic and aerosol environment within which convection initiates and progresses through its life cycle; the characteristics of the cloud fields, including shallow convection, which may play a role in moistening the middle troposphere; cirrus anvil properties; and aerosol characteristics in the Houston metropolitan region.

Critical AMF1 instrumentation [1] needed to accomplish the scientific goals of the TRACER campaign include (Priority= [1] is “essential.” Priority= (2] is “useful”):

Clouds: Ka-band ARM Zenith-pointing Radar (KAZR) [1], Ka/W-band Scanning ARM Cloud Radar (SACR) [1], ceilometer (CEIL) [(1], micropulse lidar (MPL) [1], total sky imager (TSI) [2], radar wind profiler (RWP) [1].

Aerosols and Trace Gases: CCN counter [1], condensation particle counters (CPC) [1], ultra-high-sensitivity aerosol spectrometer (UHSAS) [1], scanning mobility particle sizer (SMPS) [1], aerodynamic particle sizer (APS) [1], nephelometer [2], tricolor or continuous light absorption photometer (TAP/CLAP) [2], aerosol chemical speciation monitor (ACSM) [2], CO system [1], SO_2 monitor [1].

Precipitation: Laser disdrometer (LDIS) [1], rain gauge (RAIN) [1], video disdrometer (VDIS) [1].

Atmospheric State: Atmospheric emitted radiance interferometer (AERI) [1], Doppler lidar (DL) [1], eddy correlation flux measurement system (ECOR) [2], surface meteorological instrumentation (MET) [1], microwave radiometer (MWR) [1], radiosonde (SONDE) [1].

Radiation: Downwelling broadband shortwave and longwave irradiance (SKYRAD) [2].

AMF1 Special Instrument Operations

Ka/X-SACR: The scanning observations from the SACRs can better detect the earliest stages of deep convective clouds that are below the detectability thresholds of longer-wavelength precipitation radars (C- and S-band radars) and the low-level wind field using insects as the source of scattering. The same scan strategy is proposed throughout the field deployment, including the IOP. The SACR will perform two low-level plan position indicator (PPI) scans at 0.5° and 2.0°, at 6 °s-1 scan rate, followed by along- wind RHI scans to observe evolving cells as they propagate towards the AMF site. Deviations from this radar scanning plan will be discussed among ARM radar engineers and the TRACER science team.

Radar Wind Profiler (RWP): RWPs are proposed to operate in a fashion similar to the current RWP operations as implemented at the ARM Southern Great Plains (SGP) observatory starting in spring, 2019. These operations enable a hand-off in deep convective cloud environments between the needs of boundary-layer (BL) wind operations (longer averaging, for estimates of lower-level wind shear) and higher-temporal-resolution precipitation (PR) column sampling (detailed vertical air motion and rainfall properties) as contingent on the signatures of precipitating clouds over the RWPs. Typically, this hand-off should occur at the initial signatures of convective anvils, but may be delayed to within the first 30s of rainfall onset over the RWPs in isolated, initiating cellular events. Given the importance of calibrated reflectivity factor and vertical mean Doppler velocity estimates from these PR modes towards the estimates of precipitation rates and vertical air velocity, we recommend that the RWP is collocated with a disdrometer, monitored by the mentors/field staff to ensure the RWP remain vertically pointing throughout the campaign.

Radiosondes: To best capture the variability in boundary-layer thermodynamic structure during normal operations, we request the typical radiosonde launch schedule for AMF1 deployments of four launches per day, every six hours (nominally 0000, 0600, 1200, 1800 LT), spanning the entire diurnal cycle. During the IOP, on forecast convective days, the launch schedule would change to better capture rapid daytime development of the atmospheric thermodynamic structure with balloon launches every 1.5 hours (approx. 1200, 1330, 1500, 1630, 1800 LT dependent on forecast conditions), adding three additional sounding launches from the AMF1 (additional soundings will be launched from ANC on these days). Based on the statistics of the percentage of days each month with convective activity, we estimate 10 enhanced sounding days each month during the IOP leading to a total of 120 (4 months x 10 enhanced sounding days per month x 3 additional soundings per day) additional radiosondes beyond baseline AMF1 operations.

Aerosol Observing System: Normal operating modes of AMF1 Aerosol Observing System (AOS) instrumentation will be sufficient to achieve measurement objectives. A diethylene glycol condensation particle counter (DEG CPC) can be provided by the Co-Investigator Kuang.

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

The transportable CSAPR2 is a state-of-the-art, dual-polarization radar system suitable for the study of large-scale precipitation systems with an effective range of 120 km. The proposed location for the deployment of the CSAPR2 is (or near) Croix Memorial Park, south of the main Houston metropolitan area (Fig. 1), for the duration of the TRACER campaign. The selected location is near a Texas Commission on Environmental Quality (TCEQ) monitoring station, offers unblocked low-level radar surveillance in all directions (limited tree blockage exists to the west), and is located 30.4 km west of the NEXRAD radar. This location allows the sampling of convective clouds as they move inland and enables the radar to follow their evolution as they propagate over Houston metropolitan area.

The CSAPR2 is a research-grade scanning polarimetric radar that can provide the rapid sampling (via tracking) needed to observe the evolution of convective core properties under varying environmental conditions. During the IOP, the CSAPR2 will be used to track convective cells. It is only through tracking and measurement of individual convective cells that key processes controlling their properties can be inferred from kinematic and microphysical structures that may be time- and space-lagged with respect to the dynamical and microphysical interactions that act over time in flowing air.

During the IOP, the CSAPR2 will be operated in a manner to track and sample convective cells. A number of algorithms have been developed for identifying and tracking convective cells (e.g., Dixon and Weiner 1993; Han et al. 2009; Stein et al. 2015). The TRACER science team radar sub-group will work with ARM radar engineering and operations to define an appropriate cell-tracking algorithm to meet the TRACER science goals. Nominally, within the algorithm, the CSAPR2 will perform a low-level surveillance PPI scan (~15-20 sec) to identify convective cells based on a set of rules and thresholds and, using information from past surveillance scans, will be able to determine the movement of the cells. Subsequently, the CSAPR2 will repeat sector scans to minimize the revisitation time of the same convective cell (on the order of 2 minutes or less). The sector scan will be repeated until another low- level surveillance scan is performed and the scanning procedure is repeated. The convective cell tracking will be used to create composites of cloud life cycles in relatively clean and polluted conditions.

Outside of the IOP, the CSAPR2 will perform standard Volume Coverage Pattern (VCP) similar to those performed by the ARM CSAPR during the Midlatitude Continental Convective Clouds Experiment (MC3E) supplemented with Hemispherical Sky-Range–Height Indicator (HS–RHI) scans to examine the vertical structure of cells. The sector scan observations will allow us to resample the same convective cells frequently and thus capture their temporal evolution. In terms of measurements, high-quality polarimetric measurements are of great interest; thus, we plan to determine the scan rate of the CSAPR2 based on the number of independent samples needed to ensure high-quality measurements. In addition to the radar polarimetric measurements, we anticipate studying the low-level organization of the boundary layer, especially during sea-breeze conditions using CSAPR2-KHGX dual-Doppler analysis. In addition, we anticipate retrieving information about convective cell dynamics using the high-resolution RHI scans along the convective cell propagation (Nicol et al. 2015). In addition, 3D velocity retrievals will be possible by the CSAPR2- KHGX VCPs outside of the IOP or whenever we operate in nominal VCP mode with the CSAPR2.

3.5 Ancillary (ANC) ARM Site

During the IOP (June-September), an ancillary ARM site will be deployed with radiosonde, meteorological, and aerosol observations in the relatively unpolluted region to the southwest of Houston in Brazoria County, Texas. These measurements, in combination with those from the AMF1, will give us an understanding of the variability of aerosols and meteorology between the onshore flow and the urban Houston area. **On days that are forecast to be deep convective**, we propose launching five radiosondes at 1.5 hour intervals (approximately 1200, 1330, 1500, 1630, 1800 LT dependent on forecast conditions). We estimate the total number of radiosondes launched from the ANC site to be 200 (4 months x 10 convective days per month x 5 soundings per day).

Aerosol instrumentation for the ANC site will be provided as guest instrumentation by co-investigators. The CCN counter, DEG CPC, CPC-ultrafine (CPCU), CPC-fine (CPCF), and SMPS will be provided by Co-I Kuang. Radiosonde, surface meteorology, rain gauge, and laser disdrometer instrumentation will be provided by ARM. Should an extra ARM MWR be available, it could also be deployed, which would allow for a merged sounding value-added product (MERGESONDE VAP) retrieval at this site that could be compared with the same product at the AMF1 site, helping to quantify meteorological differences at the two sites. We expect that proposals for additional guest instrumentation will be submitted for both the AMF1 and ANC sites including: INP measurements (Co-Investigator Brooks) and optical properties and composition of carbonaceous aerosols (Cappa).

3.6 Value-Added Data Products Needs

In order to accomplish the goals of the TRACER campaign, the majority of the Core AMF1 value-added products (VAPs) that have been identified in the ARM Translator Plan (Riihimaki et al. 2018) are critical. In addition to these core VAPs, the following list of products are necessary to meet the stated science goals:

AERIoe (AERI Optimal Estimation Retrieval of Thermodynamic Profiles and Liquid Cloud Properties) — For providing boundary-layer profiles of temperature and humidity, liquid water path, and precipitable water vapor.

MERGEDSONDE (Merged Sounding) — For providing high-time-resolution estimates of atmospheric thermodynamic profiles (Troyan 2012).

VARANAL (Large-Scale Forcing Data for single-column model (SCM)/cloud-resolving model (CRM)/large-eddy simulations (LES) from Constrained Variational Analysis) — For model forcing data sets used towards parameterization development.

VISST (Visible Infrared Solar–Infrared Split Window Technique) satellite products — Geostationary satellite cloud macro- and microphysical property retrievals (https://cloudsway2.larc.nasa.gov/)

3.7 Collaborative Resources

3.7.1 Existing Infrastructure

KHGX NEXRAD with I/Q time series recorder. The operational WSR-88D radar network is a system of S-band radars in the U.S. that has been collecting data reliably for more than two decades. The KHGX radar located southeast of Houston will be supplied with a time series (a.k.a., “I/Q” or “Level 1”) data recorder to enable custom processing algorithms that retain more data and include sophisticated spectral processing to enhance signal recovery in regions of low signal-to-noise ratio (SNR). This will result in earlier detection of developing convective clouds with more data along the edges of radar echoes. In addition, the data quality of polarimetric variables in regions of very low SNR will be improved with multi-lag estimators, and high-pulse-repetition-frequency (PRF) rather than low-PRF scans will be used to improve polarimetric variable retrievals at low elevation angles. Data will also be processed to provide azimuthal oversampling at higher elevation angles. Co-Is Ryhzkov and Snyder have worked with KHGX staff to collect NEXRAD time series data and will do this again during TRACER.

Houston-area Lightning Mapping Array. The Houston-area Lightning Mapping Array (HLMA) is a network of 12 time-of-arrival, very-high-frequency (VHF) lightning sensors (Figure 1) operated and maintained by Texas A & M University (TAMU) since 2012. Using this array of sensors, 4D quantification of the lightning discharge can be obtained. The resulting charge distribution, and flash location and rate information, can be used as a proxy for convective strength and ice microphysical properties.

Texas Commission on Environmental Quality. The Monitoring Division of the TCEQ has 75 sites within the Houston metropolitan area (Figure 1) that collect continuous (5-minute resolution), semi-continuous (integrated over time), and non-continuous (e.g., filter-based measurements of particulate matter) air quality and meteorological measurements. TCEQ data are validated and certified by the technical staff. Each data point has an associated data flag indicating ambient sample, quality assurance check, preventative maintenance, etc. in order to exclude non-ambient data from being reported. Depending on data temporal resolution, hourly or daily averages are available publicly on the TCEQ website. Higher-resolution data is available by request for most measurements. TCEQ observations will provide spatial variability information that will be useful for determining air mass source attribution, background aerosol loading variability, urban heat island horizontal extent, and sea/bay-breeze propagation. Co-I Flynn has extensive experience with the TCEQ observational network.

Geostationary Operational Environmental Satellite (GOES-16) Observations. The GOES-16 Advanced Baseline Imager gives images of reflected radiation at 0.64 microns (0.5-km resolution) and emitted radiation at near-IR and IR channels (1-2-km resolution) every 5 minutes. Co-I Collis will work with contacts within NOAA to request rapid scan 1-minute sectors over the Houston region during TRACER. All GOES-16 data are freely available on Amazon Web Services.

Surface Meteorological Networks and Buoy Observations. Approximately 10 NOAA National Weather Service (NWS) (Figure 1) and ~50 Citizen Weather Observing Program (CWOP; http://www.wxqa.com/) weather stations with freely available, quality-controlled data in the Houston region will be used to characterize regional thermodynamic variability and evolution. A subset of these stations includes measurements of winds and rainfall, which along with temperature and moisture, impact regional convective cloud and aerosol variability. In addition, there are more than 10 Texas Coastal Ocean Observing Network buoys in Galveston Bay and the Gulf of Mexico that provide surface meteorological and water temperature measurements. These data are available from the NOAA National Data Buoy Center (www.ndbc.noaa.gov).

3.7.2 Evolving Partnerships and Collaborations

While the science goals of TRACER can be accomplished using the ARM assets requested with the existing infrastructure as outlined in this science plan, a number of complementary instrument suites are also being pursued that would further enhance the scientific impact of the campaign.

4.0 Project Management and Execution

The majority of the AMF1 instrumentation will operate in default modes as defined by ARM instrument mentors and the AMF1 operations team, with exceptions noted in section 3.3.

The TRACER science team will work with the ARM radar engineers to define the baseline scanning operation of the CSAPR2 and Ka-band Scanning ARM Cloud Radar (KASACR)/X-band Scanning ARM Cloud Radar (XSACR). In addition, these groups will work together to define the criteria for choosing which convective cells to track, and for how long, in order to accomplish the science goals of TRACER.

During the IOP, radar and sounding operations will change depending on forecast conditions. The principal investigator (PI) and defined co-investigators will organize the forecasting activities following their previous experience doing this for the RACORO, MC3E, SPARTICUS, Aerosol and Clouds Experiment in the Eastern North Atlantic (ACE-ENA), and Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaigns. Forecasting activities will take place online using Bluejeans or a similar screen-sharing application. Forecast teams, including scientist and student volunteers, will work on approximately two-week rotating shifts. A designated forecast team member will communicate operational plans to the ARM radar engineers and radiosonde launch teams.

4.1 Data Management Plan

Climate research data publicly funded by DOE's Office of Biological and Environmental Research (BER) are a public trust and should be freely available. The data should be preserved, documented, quality assured, and discoverable by any who request it. The section documents the process by which data, including metadata, resulting from the TRACER campaign will adhere to those basic requirements.

4.1.1 Data Sharing and Preservation

Data sets generated from ARM instrument measurements during TRACER will be quality-controlled and delivered to the ARM Data Center (www.arm.gov/data) by ARM instrument mentors. The TRACER science team will aid in the evaluation of the data quality through regular visualization of the critical datastreams during the campaign. Any data quality issues identified will be communicated to the ARM instrument mentors through the Data Quality Problem Reporting (DQPR) system. During the IOP, a log will be kept of daily forecasting activities and decisions regarding the radiosonde launch frequency and

CSAPR operating modes. This log will be archived and available via the ARM campaign website. Higher-order data products, will be produced by ARM translators (value-added products; VAPS) and TRACER science team members, under separately funded research grants. These products will be submitted as IOP or PI products to the ARM Data Center using the ARM Product Registration and Submission Tool and/or be subject to individual funding agency data-sharing policies. Data sets collected by collaborative resources (NEXRAD, LMA, TCEQ) will be archived and available from the supporting agencies. Higher-level derived products using the data from these collaborative resources produced by TRACER science team members will also be shared via the ARM Data Center. With the assistance of ARM Data Center staff, all data products generated will be assigned Digital Object Identifiers (DOIs) to facilitate citation and visibility.

Research results and the relevant data will be published and cited in peer-reviewed scientific papers. Preliminary results will be presented at domestic and international conferences as posters and/or oral presentations. All research data displayed in publications resulting from the proposed activity will be digitally accessible shortly after the manuscript is accepted for publication via its DOI. This includes all research data required to validate and reproduce published results.

4.1.2 Data Types, Sources, Content, and Format

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

5.0 Science

Many previous studies highlight persistent convective system dynamical and microphysical biases within models (e.g., Varble et al. 2014a, Stanford et al. 2017). Causes for model biases, including overly strong updrafts and excessive supercooled liquid, riming, and large ice particles, remain inconclusive because dynamical and microphysical feedbacks obscure errors in initiating convective cells that could be subtle. Convective biases can cause insufficient development of stratiform precipitation (Varble et al. 2014b) and potential biases in the vertical transport and detrainment of heat, moisture, momentum, and aerosols. Finding root causes for these persistent model biases requires tracking the detailed evolution of a large number of individual convective cells from initiation to decay, a primary objective of TRACER that differs from past field campaigns. This will allow identification of specific locations and times within the convective life cycle where models and observations diverge in a consistent manner so that model sensitivity studies can be designed to identify processes that impact that divergence, potentially leading the way towards improving representation of those processes.

Analysis will include the use of the polarimetric radar observations to quantify the evolution of the dynamical and microphysical properties of the convective core and nearby storm elements over the course of the storm life cycle. This analysis will focus on the differences in these characteristics under varying environmental forcing, surface conditions, wind direction, and aerosol regimes. An integrated modeling component will use derived forcing data sets to simulate the deep convective cases at CRM scales. A main target is to identify cases with observed differences in isolated convective microphysics where there is a significant aerosol perturbation within a relatively uniform thermodynamic environment with winds from similar directions. These cases will then be used to evaluate our ability to simulate these signatures using CRMs. For example, convective cell tracking will be used to create composites of cloud life cycles in relatively clean and polluted conditions, under similar environmental forcing, to determine how different aerosol concentrations change the properties of the isolated deep convective clouds in both the observations and the simulations. Coordinated modeling studies will build upon the ongoing deep convective modeling intercomparison studies of the Aerosol, Clouds, Precipitation, and Climate (ACPC) group (van den Heever et al. 2018). These efforts are critical to achieving a process-oriented understanding to assist in untangling how much of the changes in cloud properties are caused by the aerosols themselves, or by changes in meteorological or surface forcing that may also be affecting the aerosol properties. Prior modeling studies have also demonstrated that variations in environmental moisture, wind shear, and CAPE (Khain et al. 2008; Fan et al. 2009; Storer et al. 2010) may modulate the aerosol impacts on convection. Carefully planned sensitivity simulations may therefore also help to determine the impact that aerosols may have on the cloud properties, and that the changing cloud properties may have on the transport and cloud-processing of the aerosol themselves. The ACPC DCC working group is currently focusing on conducting such a suite of sensitivity simulations employing a number of different CRMs with the primary goals of determining:

1. the variability of the atmospheric response, both locally and regionally, to aerosol perturbations among various state-of-the-art CRMs; and
2. which physical processes are the most significant contributors to aerosol-induced uncertainties in current CRMs, in terms of representing aerosol-cloud-precipitation-climate interactions.

Another objective of the proposed field campaign will be to advance robust evaluation and improvement of state-of-the-art, high-resolution model skill in representing updraft dynamical and microphysical processes, which remains markedly lacking in some basic aspects (e.g., Fridlind et al. 2017; White et al. 2017). High-resolution model simulations of deep convective clouds are very sensitive to the choice of different cloud microphysics parameterizations (Fan et al. 2017), and the uncertainty between different microphysics schemes is often larger than aerosol impacts (White et al. 2017). Therefore, evaluating and improving cloud microphysics parameterizations with cloud dynamics and microphysics observations is particularly imperative in accurately modeling clouds and aerosol impacts. In addition, data sets adequate to advance high-resolution model skill are also frequently well suited to improve climate model representation of convective and microphysical processes. The ultimate goal will be the generation of an integrated data set that is adequate to guide improvement of model physics of deep convective storms under varying aerosol conditions, suitable to be used for physics understanding and parameterization development for both high-resolution and climate modeling communities. Such a data set would, for example, be highly useful in evaluating the kinds of ACPC DCC working group multi- model CRM sensitivity simulations.

The combination of a multi-model ensemble of cloud-resolving simulations and the TRACER observations of a large set of convective clouds will also be used to attempt a detection-attribution study for aerosol-cloud interactions. The hypothesis is that there are specific observables for which the set of simulations with best-guess aerosol concentrations is significantly closer to the TRACER observations than the set of simulations excluding the Houston pollution plume. To the extent this is consistent across models and explainable by identified aerosol-cloud-precipitation interaction processes, such a detection-attribution study may allow us to draw strong conclusions about a causal relation in aerosol-cloud interactions.

By measuring convective updraft speeds and pre-storm aerosol and meteorological conditions at a downwind site over a one-year period, a large number of convective cells will be sampled. We will analyze and compare them based on the similarity and differences of the pre-storm aerosol and meteorological conditions using methodologies similar to those in Fan et al. (2018) and Varble (2018). This statistical analysis will potentially allow us to detect an aerosol impact on clouds that is separate from first-order meteorological impacts.

In addition, we request that ARM generate large-scale forcing data from constrained variational analysis during the IOP period of TRACER. Large-scale forcing will be used for driving model simulations at different scales, from LES to CRMs to SCMs. This approach is long-established to compare the physics process and parameterization development of LES/CRMs/SCMs (Randall et al. 1996, Waliser et al. 2002, Xu et al. 2002). TRACER observations and CRM model intercomparison will allow narrowing down of the physics suites of CRM/LES simulations of deep convection. The resulting observation-constrained, high-quality CRM/LES databases will enable further development of physics parameterization in climate models to improve convective dynamics and associated precipitation and radiation budgets.

By combining the surface meteorological measurements and sounding data with boundary and convective cell measurements, we will look at the variability of meteorological conditions and identify different bay- and sea-breeze conditions and their associated aerosol properties. We will also examine how Houston urban lands impact local circulation, deep convective initiation location/timing, and deep convective life cycle properties.

6.0 Relevancy to the Mission of the DOE Office of BER

The Biological and Environmental Research Advisory Committee's recently released Grand Challenges report (DOE BER 2017) states several action items within the Earth and Environmental Sciences subtopic to which the TRACER campaign science goals are directly relevant. In particular, these action items include:

1. To advance high-resolution modeling in different simulation and prediction modes supported by exascale computing to improve understanding and prediction of extreme or high-impact events,
2. To develop and integrate new sensing technologies and optimize field deployments in ARM, etc. to explore interactions across different scales of biological organization and biosphere-atmosphere feedbacks, and
3. Create new integrated field laboratories that target biogeochemical, energy, and water flows between urban areas and surrounding ecosystems.

The focus of TRACER on advanced radar applications for the detailed study of convective clouds in a coastal urban environment towards the goal of improving high-resolution simulations of the relevant atmospheric processes falls within each of these action items.

The DOE ARM mission focuses on providing "… the climate research community with strategically located in situ and remote-sensing observatories designed to improve the understanding and representation, in climate and Earth system models, of clouds and aerosols as well as their interactions and coupling with the Earth's surface (DOE ARM 2014)." Accurately representing convective cloud dynamics and microphysics remains one of the greatest challenges for modeling studies over a wide range of scales. The quantification of aerosol impacts on convective vertical velocities, precipitation, and microphysics remains elusive, with different studies finding contrary results (Tao et al. 2012). The proposed field experiment is expected to provide unique, high-temporal-spatial-resolution microphysical and dynamical observations that are needed to investigate the role of aerosol in altering deep convection intensity and evolution using a combination of observational and modeling analyses. In support of this goal, the proposed campaign will focus on the characterization of convective cloud properties and the convective environment with an emphasis on cloud-scale dynamics and microphysics, particularly in the updraft region under different aerosol loading conditions. If funded, the proposed field campaign would be the first deployment of ARM mobile facilities in the United States to focus on aerosol impacts on deep convective clouds. Following the successful GoAmazon field experiment on this topic, this field campaign is designed to gain further understanding on storm structure and microphysical processes and how they are influenced by aerosol properties based on observational data, which would lead to a leap in our understanding.

7.0 References

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