# Aerosol, Cloud, Precipitation and Climate (ACPC) Initiative
# Deep Convection Cloud Roadmap: TRACER and follow-on Activities

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The Aerosol, Cloud, Precipitation and Climate (ACPC) working group (http://acpcinitiative.org) is a joint initiative of the International Geosphere–Biosphere Programme (IGBP) and the World Climate Research Programme (WCRP), developed through the cooperation of the IGBP's Integrated Land Ecosystem–Atmosphere Processes Study (iLEAPS) and International Global Atmospheric Chemistry (IGAC) and WCRP's Global Energy and Water Cycle Experiment (GEWEX). The ACPC working group aims to improve our scientific understanding of the interactions among aerosol, clouds, and precipitation at a fundamental level towards improved understanding and simulation of the climate system. Towards this goal, the ACPC working group is organized around two cloud regimes, one targeting shallow clouds and their study using "natural laboratories," and another targeting deep convective clouds. This roadmap lays out the science plans within the ACPC deep convective clouds initiative with a particular focus on observational and modeling studies centered around the upcoming TRacking Aerosol Convection interactions Experiment (TRACER; Jensen et al. 2019) and associated field campaigns.

## 1. Introduction

Deep convective clouds (DCCs) play a critical role in precipitation, radiation, and the general circulation (e.g., Sherwood et al., 2014). Aerosol-mediated cloud radiative forcing remains the largest uncertainty in anthropogenic perturbation to the climate system based on the most recent IPCC report (IPCC, 2014). Significant progress in our understanding of aerosol impacts on DCC microphysics, dynamics, and radiative properties has been made over the past ~20 years, mainly based on theoretical and process-level modeling studies (e.g., Tao et al. 2007; Fan et al. 2016; and the references therein). These studies have suggested that CCN active aerosol particles (diameter > 50 nm), through their impact on hydrometeor size distributions, can suppress warm rain processes and enhance the water mass available for freezing, resulting in an enhancement of latent heat release from freezing and the subsequent ice growth processes through deposition and riming, warming the rising convective parcel, inducing stronger and deeper convective updrafts (e.g., Khain et al., 2005; van den Heever et al., 2006; Rosenfeld et al., 2008; Fan et al. 2012). Meanwhile ultrafine aerosol particles (diameter < 50 nm) may strengthen convection and precipitation through the enhancement of condensation in warm and humid environments (e.g., Khain et al. 2012; Koren et al., 2014; Sheffield et al., 2015; Fan et al., 2018, Chen et al. 2020). Aerosol-DCC interactions may also notably affect cloud radiative forcing through changing fractional coverage and the thickness of the stratiform and anvil components of DCCs (e.g., Koren et al., 2005; Fan et al., 2013; Saleeby et al., 2016). In addition, aerosols have been linked with enhanced lightning in DCC systems (e.g., Mansell and Ziegler 2013; Altaratz et al., 2017). Although invigoration of convective updrafts by aerosols through enhanced latent heating from condensation and freezing and subsequent ice growth processes are supported by both theoretical analysis (Rosenfeld et al. 2008; Pinsky et al. 2013; Fan and Khain, 2021) and explicit modeling (e.g., Khain et al. 2005, 2012), the significance can vary because of the compensation and buffering effects from various atmospheric processes such as cloud adjustment (Stevens and Feingold, 2009), the convective–radiative quasi-equilibrium relationship (Grabowski and Morrison, 2011), and covariability of meteorological variables (Varble, 2018). The magnitude and sign of aerosol effects on DCC depends on the aerosol chemical and physical properties, meteorological conditions, and storm types as summarized in the review papers (Tao et al. 2012; Fan et al. 2016). A new study suggests that the aerosol-cloud-environment interaction could increase environmental humidity due to enhanced droplet evaporation in a polluted condition, favoring stronger convection (Abbott and Cronin, 2021). The fixed droplet number and two-moment cloud microphysics scheme employed over a small closed domain poses questions to the study but it pointed to another possible mechanism for convective invigoration over a time scale beyond the cloud lifecycle. Despite recent advances in our understanding, a lack of comprehensive observations over a range of aerosol properties, thermodynamic and kinematic environments, and convective microphysical and dynamic properties poses a significant obstacle in preventing us from confidently isolating and quantifying aerosol effects on clouds, precipitation and climate.

This roadmap builds upon previous efforts within the ACPC Deep Convective Cloud (DCC) Working Group that conducted a multi-model intercomparison project (MIP) focused on simulations of a case study of isolated deep convective clouds in and around the Houston, Texas region. Observations from operational ground- and satellite-based platforms were used to evaluate the simulation results (van den Heever et al., 2017). Several important conclusions are drawn from the ACPC MIP studies:

- Diversity in parameterization of cloud and precipitation microphysics results in variability of simulated total accumulated precipitation that is larger than the differences under varying aerosol conditions. (van den Heever et al., 2019).
- For enhanced aerosol concentrations, there were encouraging similarities between model demonstrated decreases in accumulated precipitation, rain mass, raindrop number concentration and downdraft velocities, and increases in cloud mass, cloud droplet number concentrations, raindrop diameters, anvil ice mass,

anvil extent, and updraft velocities within the warm phase region (van den Heever et al., 2019).

- A number of important differences were also found among the models within the intercomparison effort. For example, models varied significantly in terms of anvil ice mass amounts. Similarly, there was no general agreement in the sign of the response of updraft velocities within the mixed and ice phase regions, or the intensity of cold pools to increased aerosol loading. (van den Heever et al., 2019).
- An in-depth evaluation of aerosol impacts on the updraft characteristics of the numerous convective updrafts simulated by the 7 models of the MIP has been conducted by examining aerosol impacts on each of the terms of the vertical momentum tendency equation (Marinescu et al., 2021). All of the models revealed enhanced thermal buoyancy (due to condensational heating) and hence stronger updrafts between cloud base and ~5 km AGL under high-CCN conditions. Between 5 and 8 km AGL, the differences between the high- and low-CCN cases were reduced in most of the models due to the drying of the updrafts. Above 8 km AGL the updraft responses to enhanced aerosol loading diverged, and appears to be associated with aerosol impacts on the vertical pressure perturbation gradient.
- A detailed analysis of microphysical process rates for composites in two of the models (WRF-Morr and RAMS) of tracked convection shows that there is good agreement between the two models for warm-phase processes and the response of shallow convective clouds. However, there exist large persistent differences in the evolution of mixed- and ice-phase microphysical processes between the two models (Heikenfeld et al., 2020).

Other studies and important conclusions by ACPC DCC group include:

- The investigation of Houston urban land and anthropogenic aerosols suggests that the anthropogenic aerosol effect on convective intensity and precipitation of a storm is more significant than the urban land effect. However, the latter modifies convective evolution by enhancing sea breeze circulation which leads to a faster development from the warm cloud to mixed-cloud stages (Fan et al., 2020). Based on the same storm case, another study using WRF-Chem coupled with a two moment bulk microphysics scheme and a bin scheme and showed that that physically representing droplet condensational growth and evaporation is very important for simulating aerosol-cloud interactions (Zhang et al., 2021).
- Observational analysis suggests an increase in radar echo top height and lightning flash count with increasing cloud condensation nuclei (Hu et al., 2019).
- Comparison of polarimetric radar observations of convective cells, above and below the melting layer, with forward-simulated values will likely lead to significant progress in our understanding of influences on cloud and precipitation microphysics (Fridlind et al. 2019).

- Owing to the rapid evolution of isolated convective cells, higher resolution polarimetric radar observations, in time and space, compared to operational NEXRAD are necessary to gain relevant insights into the relevant microphysical processes (Fridlind et al. 2019).
- Continued advancements in dual-polarization radar microphysical and thermodynamic retrievals in ice and rain may provide much needed information about the characteristics of hydrometeors, as well as warming / cooling rates due to diabatic processes (Ryzhkov and Zrnic 2019; Ryzhkov et al., 2020).

A major takeaway from these ACPC-led efforts is that to advance our understanding of aerosol-convection interactions, ***there is a need for a coordinated measurement and modeling approach employing a combination of high-resolution, in time and space, observations of convective cloud microphysics, environmental thermodynamics and kinematics, and aerosol chemical and physical properties with an ensemble of state-of-the-art cloud-resolving model simulations representing the diversity of microphysical representations*.** The Houston area was identified as an ideal testbed for deploying this strategy since it offers: (a) a combination of polluted aerosols from the urban and industrial area of Houston with significantly low background aerosol concentrations in the surrounding region, (b) aerosol sources that are not correlated with meteorology, and (c) weak synoptic forcing along with strong local triggering in the form of land-sea contrasts and sea breeze fronts. This combination allows the manifestation of potentially large aerosol effects on convection (Zhang et al. 2021). The TRacking Aerosol Convection interactions ExpeRiment (TRACER; Jensen et al. 2019) was proposed and selected by the U.S. Department of Energy's (DOE) Atmospheric Radiation Measurement (ARM) program (Mather and Voyles 2013). The TRACER campaign will take place from 01 October 2021 through 30 September 2022, with an intensive operational period (IOP) from June through September 2022. The major objective of the campaign will be the detailed observation of isolated convective cells throughout their lifecycle in varying aerosol and thermodynamic conditions during the one-year period, with special emphasis during the TRACER IOP. In addition, the National Science Foundation's Experiment of Sea Breeze Convection, Aerosols, Precipitation and Environment (ESCAPE) campaign will contribute remote sensing and aircraft in situ measurements of clouds, precipitation and aerosols relevant to ACPC objectives during the summer of 2021. Prior to, and during, the IOP of TRACER, interagency partners from the NSF, the National Aeronautics and Space Administration (NASA), the Texas Commission on Environmental Quality (TCEQ) and the National Oceanic and Atmospheric Administration (NOAA) will contribute additional measurements that enhance the study of aerosol-convection interactions and expand to include related scientific studies.

## 2. Key science questions to be addressed

The overarching science questions motivating research within the ACPC Deep Convective Clouds group include:

(1) To what extent, under what conditions and through which physical pathways do aerosols influence convective updraft intensity, anvil cover, and precipitation amount and rate?
(2) Which physical processes are the most significant contributors to aerosol-induced uncertainties in the feedback to cloud dynamics in current cloud-resolving models (CRMs)?
(3) How is radiative forcing at the top-of-atmosphere (TOA) and the surface mediated by aerosols through aerosol-cloud interactions? (For deep convective clouds, the question is how aerosols change cloud stratiform/anvil properties and water vapor content at upper levels, both of which affect radiative forcing)
(4) What observations (spatially and temporally) are required to provide accurate estimates of energy, moisture, and aerosol fluxes to the scales of a GCM grid box?

The specific science questions associated with TRACER field campaign include:

(1) What are the necessary spatial-temporal constraints required to document and understand the dynamics in DCC and its interactions with microphysics and aerosols?
(2) How do aerosols and convective cloud properties vary across the Houston region and how do aerosols co-vary with meteorological conditions?
(3) 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)?
(4) How do aerosols affect the height and type (raindrops or ice particles) of precipitation initiation, total precipitation, and lightning activity?
(5) What are the roles of anthropogenic aerosols and the urban land surface in modifying local circulations, deep convective initiation location/timing, and convective cell evolution, and precipitation?
(6) How are aerosol-deep convection interactions via cloud microphysical processes best represented in global and regional climate models?

## 3. The TRACER Campaign

The TRACER campaign will take place in the Houston, TX region from 01 October 2021 through 30 September 2022, with and IOP from June-September 2022. The campaign includes the deployment of: (1) the First ARM Mobile Facility (AMF; Miller et al., 2016) will be deployed in an area experiencing significant aerosol loading from local industry and transportation sources (among others), providing a full suite of in situ and remote sensing observations of cloud, aerosol, radiation, precipitation and thermodynamic state for the entire campaign, (2) the 2nd generation C-band Scanning ARM Precipitation Radar (C-SAPR2), deployed for the entire campaign, will be focused on automated tracking of isolated convective cells during the IOPs and (3) an ancillary site will be deployed to the southwest of the Houston metropolitan region, during the IOPs, with the goal of capturing the background atmospheric state, i.e., assumed to not be significantly influenced by urban pollution sources, thereby providing the opportunity to compare moderate versus polluted conditions.

In addition to the year-long deployment by the DOE ARM facility, additional measurement platforms will be participating prior to and during the TRACER campaign observational period:

- The **NSF Experiment of Sea Breeze Convection, Aerosol, Precipitation and Environment (ESCAPE)** campaign will focus on several scientific topics that are closely related to ACPC and TRACER objectives including: Aerosol indirect effects on the early growth stages of convective clouds, coastal convective initiation, the lifecycle of convective updraft microphysical and kinematic properties, environmental thermodynamic and kinematic controls on convective lifecycle, convective cold pol variability and lightning flash size and energy. The ESCAPE airborne campaign is scheduled to take place mid-June through mid-July 2022 and includes 90 flight hours for the NCAR C-130 equipped with in situ microphysical probes, aerosol measurements of CCN, INP and biological aerosols, air motion sensors and a cloud radar and 32 flight hours for the SPEC Learjet 35A equipped with state-of-the-art microphysical probes, air motion sensing and a cloud radar. The ESCAPE airborne measurements will provide important constraints on vertical distributions of cloud condensation nuclei and cloud microphysical properties that are needed to accomplish ACPC science goals. The ground-based portion of the ESCAPE campaign is scheduled to take place from 10 June through 25 July and includes the deployment of additional radar platforms (CSU C-band radar, OU Mobile X-band radars), multi-instrument mobile remote sensing platforms (SBU Weather truck, BNL research truck), upgrades to the Houston Lightning Mapping Array and additional radiosonde and swarmsonde (Markowski et al. 2018) measurements. These additional measurements of convective updraft polarimetry and kinematics, boundary layer structure and vertical thermodynamic profiling, both of the environment and within the convection, will provide important constraints for ACPC convective modeling studies.

- The DOE **Atmospheric System Research (ASR) program** has also funded an additional 10 projects to further quantify the characteristics of aerosols, clouds, and the atmospheric state in the Houston region. In particular, aerosol lifecycle studies include measurements of aerosol precursors and new particle formation, characterization of carbonaceous aerosols, local mapping of aerosol size, number and concentration, aerosol hygroscopic growth, mixing state and CCN concentrations and size-resolved eddy covariance particle flux measurements. Additional cloud lifecycle focused projects include measurements of boundary layer thermodynamic and wind properties for the study of interactions of the coastal urban boundary layer with convection, boundary layer profiling with unmanned aerial vehicles to capture sea breeze and cold pool development, and mobile measurements of cloud and thermodynamics.
- The **NASA Global Precipitation Measurement (GPM) Mission** will deploy the N-Pol S-band radar with the goal to collect dual-wavelength measurements (with CSAPR2) to improve precipitation drop size distribution parameters and improved phase discrimination.
- A complementary air quality campaign **NASA TRACER-Air Quality (AQ)** with additional contributions from the **Texas Commission on Environmental Quality (TCEQ)** will bring additional airborne and ground-based assets to the Houston region during the month of September 2021 to measure air quality relevant constituents at high spatial and temporal resolution. This deployment will focus on three specific science areas: (1) ozone photochemistry and meteorology, (2) modeling and satellite evaluation and (3) intersection of air quality and socioeconomic factors. Aircraft-based measurements will include observations of ozone precursors (NO2 and HCHO columns) from the GEOCAPE Airborne Simulator (GCAS) and ozone and aerosol profiles from the High Spectral Resolution Lidar-2 (HSRL-2). Surface-based remote sensing observations will include profiles of ozone concentration from the tropospheric ozone lidar network (TOLNET) and columnar measurements of NO2, ozone and HCHO from Pandora spectrometers.

In addition to the field campaign datasets, observations from existing operational networks in the Houston area will provide important contextual information.

- The **TCEQ** air quality monitoring network provides measurements of: gaseous pollutants, particulate matter, surface meteorology, solar radiation, at 75 sites within the Houston metropolitan area.
- The **Houston-area Lightning Mapping Array (HLMA**), including 12+ nodes, is operated by Texas A & M University and provides 4D quantification of lightning discharge, charge distribution, flash location and flash rate.

- The **HoustonNet GPS Network** includes more than 130 sites in the Houston area and provides a retrieval of precipitable water vapor.

The relevant agencies (DOE, NSF, NASA, TCEQ) and principal investigators will handle all the preparation for deployment of their instrumentation (site preparation, shipping and transportation, set-up). The TRACER/ESCAPE/TRACER-AQ Science teams, and ACPC working group will play important roles in providing forecasting guidance during the campaign, selecting case studies for detailed analysis, developing integrated datasets to facilitate aerosol-convection interaction studies and further evaluation of simulations of Houston-area convection.

## 4. Pre-campaign modeling and analysis

Pre-campaign modeling and analysis studies will focus on continued analysis of the ACPC model intercomparison project results, further exploration of the impacts of diversity in parameterization of cloud microphysics on simulated aerosol-convection interactions, and characterization of the influences of the urban landscape and sea/bay-breeze circulations on convection and aerosol-convection interactions.

**Continued analysis of the ACPC model intercomparison project** - The abovementioned ACPC MIP project led by Sue van den Heever provides a strong blueprint for evaluating model simulations of the isolated DCC over the Houston region. Although simulations from different models or microphysics schemes displayed a number of encouraging similarities in response to enhanced aerosol loading as detailed above, there are a number of significant differences that were also observed including a wide range in detrained ice mass amounts, different responses of cold pool strengths to aerosols, a wide range in updraft velocities within the mixed and ice phase regions, and differences in accumulated precipitation that varied more as a function of model physics than aerosol forcing.

These differences revealed from the ACPC MIP contributed, in part, to the formulation and design of TRACER. Analysis of these simulation results, in particular the microphysical and dynamical processes, will continue to inform campaign measurement strategies, and post-campaign analysis and modeling.

**Impacts of the Parameterization of Cloud Microphysics on Simulated Aerosol-Cloud Interactions** - The representation of cloud microphysics in models is one of the factors leading to the large uncertainty in aerosol-cloud interactions (e.g., Khain et al. 2015). A very recent study carried out for the Houston area investigating the impacts of anthropogenic aerosols from Houston on the convective intensity and precipitation of a thunderstorm (the same case as the ACPC model intercomparison project), using the Chemistry version of the Weather Research and Forecast (WRF) model (WRF-Chem) coupled with the two-moment Morrison (bulk) scheme and spectral-bin microphysics (SBM) (Zhang et al. 2021). This work identifies a significant deficiency in the bulk scheme commonly used in models to simulate ACI and presents an approach to fix the problem, that is, employing a prognostic supersaturation for condensation and evaporation calculations. The insights gained from here informed the importance of obtaining observed cloud microphysics and dynamics data in convective cells to accurately parameterizing the major microphysics processes and evaluating the parameterizations. This pre-campaign study also will provide a framework for a future model intercomparison project with a TRACER case using a variety of cloud microphysics schemes.

**Urbanization-induced land and aerosol impacts on sea breeze circulation and convective precipitation -** Urbanization changes land cover types and aerosol properties. Many previous studies have examined the impacts of either urban aerosols or urban land on convection and precipitation (e.g., Borys et al. 2000, 2003; Ramanathan et al. 2001; Diem and Brown 2003; Givati and Rosenfeld 2004; Jirak and Cotton 2006;Van den Heever and Cotton 2007; Carrió et al. 2010); (2) increased surface roughness which enhances surface convergence over and downwind of the urban region (e.g., Craig and Bornstein 2002; Rozoff et al. 2003;); (3) the urban canopy which diverts storms around these regions (e.g., Bornstein and Lin 2000); (4) enhanced sources of moisture (e.g., Dixon and Mote 2003); and (5) sensible and latent heat fluxes (e.g., Changnon et al. 1981; Shepherd et al. 2002; Shepherd 2005). Houston has been the focus of a number of these previous studies (e.g., Fan et al. 2007; Carrio and Cotton, 2011; Chen et al. 2011). Few studies have considered the effects of both urban aerosol and urban land properties on convective properties (Zhong et al. 2015, 2017; Schmid and Niyogi, 2017). The joint and relative importance of these impacts remains uncertain. Using the same case as the ACPC model intercomparison project, a new modeling study find that urbanization in Houston notably enhances storm intensity and precipitation, with anthropogenic aerosol effects being more significant than urban land effects (obtained by replacing urban land with the surrounding crop land). The urban land effect modifies convective evolution by initiating the mixed-phase cloud and surface rain earlier by ~30 min because of a strengthened sea breeze circulation.

These findings are consistent with previous investigations into the impacts of urban aerosols on convection developing in and around Houston (Carrio and Cotton, 2011) and St. Louis, Missouri (van den Heever and Cotton 2007). The former study demonstrated significant intensification of convective clouds downwind of Houston with increasing aerosol concentrations, and that storms that are already raining may produce even more precipitation as they move over Houston (Carrio and Cotton 2011). In the latter study it was shown that urban-forced convergence downwind of the city, rather than the presence of greater aerosol concentrations, determines whether storms actually develop downwind of the city, but that urban-enhanced aerosols can exert a significant effect on the microphysical, dynamical and precipitation processes once convection has initiated (van den Heever and Cotton 2007). Both of these studies point to the role played by the background aerosol concentrations. These results will help guide the sampling strategies of TRACER in order to obtain observational evidence (e.g., the importance of obtaining cell and circulation evolution data and ultrafine aerosol data, and importance of sampling data in the upwind, urban center, and downwind for urban land effect on circulation).

## 5. Post (and concurrent) campaign research activities

Post (and concurrent) campaign activities will begin with the characterization of data quality, and development of value-added products from the data collected during both the full campaign and the IOP. Efforts will be aimed at quantifying the cloud, precipitation, aerosol, thermodynamic, kinematic and electrical conditions over the entire campaign. Based on the availability of high-quality datasets, active convective conditions and variable thermodynamic and aerosol conditions a number of “golden cases” will be identified for detailed analysis and modeling by the ACPC community.

### First-order campaign data analysis activities

Some specific first-order data analysis activities are necessary to address and improve our understanding of aerosol-convection interactions and will include:

- Characterization of aerosol properties (including size distribution and composition, and CCN activity) and meteorological conditions (particularly kinematic and thermodynamic forcing characteristics), enabling first-order correlation analysis and regime identification.
- Quantify variability of convective properties (e.g., precipitation, core properties, vertical velocity, lightning flash properties) according to lifecycle markers provided by cell tracking efforts including co-location with aerosol and thermodynamic characteristics.
- Development of integrated datasets: The development of integrated (in space and time) datasets within both Eulerian and Lagrangian (with respect to tracked convective cells) frameworks, among aerosol properties, meteorological conditions, radar observations, and lightning information, will expedite scientific discovery.
- Identification of “golden cases” for focused modeling studies. This activity will include defining dates and relevant cases where isolated convective cells were observed shortly after initiation, through their growing to mature phases. In

addition, these cases will require that critical observational platforms, including those measuring cloud, precipitation, aerosol and environmental characteristics, were operating consistently with well characterized calibration and data quality. Several golden cases should be identified spanning a range of aerosol, environmental and convective conditions.

**“Golden” case simulations**

Following the identification of isolated convection case studies with high-quality observational datasets, the following modeling activities may be organized.

- Carry out CRM/LES studies targeting convection-aerosol interactions (e.g., accumulated precipitation, echo-top height, convective vertical velocity), and compare with observed results. Forward simulators (including convective cell-tracking, polarimetric radar observables, and lightning) can be applied to these simulations. The relationships of convective properties with CCN properties from the model results will be compared to the ones derived from observations under the same environments.
- Following the ACPC model intercomparison project, a “golden case” selected from TRACER will be used as the modeling target for a similar diversity of simulations. Additional observational metrics available from the TRACER measurements will help to better identify each model’s deficiencies and measure model performances. Sensitivity tests over different microphysical and planetary boundary layer schemes (also different resolutions, forcing, etc.) can be performed to compare the results across the models. To ensure the robustness of results, ensemble simulations may be conducted with different initial and boundary meteorological conditions (Miltenberger et al. 2018).
- Organize and conduct an intercomparison study with different microphysics schemes and various aerosol scenarios for a well-observed case selected from the field campaign for the WMO International Cloud Modeling Workshop (ICMW) 2024. This will be different from the approach of the ACPC model intercomparison project in which the participating models differed in dynamical core, physics parameterizations, and model configurations such as dynamics and physics time steps. In order to study major differences in cloud properties and aerosol-cloud interactions produced by different microphysical schemes and examine dominant underlying factors responsible for these differences, we propose to constrain dynamical core, model considerations, and other physical parameterizations except varying cloud microphysics schemes. This approach proved to be effective in identifying major microphysical processes responsible for the model

discrepancies in updraft intensity and stratiform precipitation for an MC3E squall line case (Fan et al. 2017; Han et al. 2019).

- Integrating with the observational analyses, perform model simulations of well-observed cases with varying urban heating, sea breeze circulation, and aerosol properties including size distribution, composition, and spatial heterogeneity. For these cases, conduct high-resolution simulations with chemistry to investigate (1) impacts of aerosol chemical properties and spatial heterogeneity on meteorology and clouds, (2) urban land and anthropogenic aerosol effects on the sea breeze induced storms and precipitation, and (3) roles of aerosol particles of different sizes and number. The corresponding model simulations can be designed to study the major processes responsible for the feedback.
- Compare lightning observations (e.g., Bruning and Thomas 2015) to forward modeling of lightning to characterize the relative activation of mixed-phase precipitation processes and their accuracy in simulations. A range of complexity is possible. In the simplest case, use warm and cold cloud classification (e.g., Stier classification) to compare to fraction of tracked cells with lightning. For more complex investigations use bulk flash rates from simulations with bulk microphysics (McCaul et al., 2009, Dahl et al., 2011a,b, Lopez 2016, Allen et al., 2016). Some of these simulations may be suitable for post-processed inference from saved microphysics fields. Finally, include the most complex case of direct simulation of electrification and discharge rates (MacGorman et al., 2001, Fierro et al., 2013, Mansell and Ziegler, 2013, Brothers et al., 2018).
- Combining ground-based radar and lightning measurements for convective cores (Fridlind et al., 2019; Wang et al. 2020) with satellite radiance and lightning observations to constrain stratiform and anvil cloud properties (Feng et al., 2011, 2019) with aerosol and dynamic and thermodynamic conditions. Conduct modeling study to examine impact of aerosols on cloud lifetime and radiative forcing. This would provide guidance for a future field campaign focusing on cloud radiative forcing.

**Lagrangian analysis of modeling and observational datasets**

To better understand the processes that drive convective lifecycle and determine the time-evolving characteristics of convection, a new combined model/measurement approaches are needed. One approach that focuses on these time evolving processes and properties is the tracking of convective cells in both model output and measurements providing cloud centric Lagrangian evolution cell properties and, through dual polarimetric capabilities of most operational and associated environments. This makes quantifying aerosol-convection interaction for different cell environments and lifecycle stages possible, in particular, applying the same cell tracking algorithm to both observations and model simulations enables consistent comparisons between them. A volume of space (latitude, longitude, depth) containing either observed or simulated storm systems can be considered as a collection of moving objects with some temporal coherence from one time-step (simulated or observed) to the next. Bulk analysis of the volume would convolute storms in various stages of evolution. By identifying and tracking cells, storm evolution can be studied in a Lagrangian frame of reference.

There are a number of different cell-tracking techniques, applications and software packages (e.g., Fridlind et al. 2019; Heikenfeld et al. 2019, Feng et al. 2018, Hu et al. 2019b) that have already been used in previous ACPC pilot study analyses. With such a menagerie of frameworks it is important for use in ACPC that these are clearly documented and compared. Cell tracking code and subsequent convective-cell track relative Lagrangian analysis can be used on model output, radar and satellite measurements and, perhaps most effectively both. Lifecycle statistics (distribution of cell lifetime and track length) derived from radar can be used as targets for simulation studies and tracking algorithms can then be used to draw insight from the model fields. For example, what is the relationship between cell age and updraft width/height? To this end this roadmap includes three activities:

1. The creation of a repository with provisioned data from several case studies (radar, satellite and model) with a plurality of aforementioned tracking codes installed. This will allow stakeholders to easily execute the cell tracking code, compare results and investigate the sensitivity of cell tracks on tracking parameters (e.g., reflectivity threshold for cell/no cell).
2. Application of a number of codes to the KHGX NEXRAD radar near Houston for the duration of the TRACER ARM AMF deployment creating a ***cloud atlas*** which identifies every cell that enters the tracer domain. Each cell will be characterized not only for its centroid, but for its spatial extent across 2D and 3D gridded fields This will allow coordinated analyses of different case studies and a common language identifying which cells were analyzed, and the spatial extent over which other observations should be paired with a cell. Initial studies linking radar detected convection to GOES 16 (or other geostationary platform) 10.3 micron cloud top temperature has been complicated by upper level clouds decoupled from parent convection which can propagate in a direction contrary to storm motion. However, there may be value in linking radar detected cells to those seen from satellites especially in studying precipitation onset and overshooting tops for maximum rain rates and hail.
3. For periods where fields of isolated convection occur, ensemble (initial conditions, perturbed physics) numerical modeling of the convective field and forward modeling radar observables will be performed. For these cases, convective cell-tracking will be applied to both modeled and observed radar observables. Use the

measurements and the ensemble simulation output, the distributions of cell properties and lifecycles in both data sets will be compared to select the model run that most closely resembles the naturally occurring convective field. Using the best simulations, an in-depth Lagrangian lifecycle analysis of that model field looking at the properties of storm kinematics and microphysics and how they vary with thermodynamic and aerosol conditions will be performed. This approach uses the cell lifecycle properties as an ***observational target*** for the modelling study to achieve. While this, alone, cannot ensure that model fields accurately represent the state of the atmosphere it does provide an additional check alongside other validation techniques.

## 6. Data Storage and Timeline

All data collected by the ARM program during the TRACER campaign will be freely available to the community via the ARM archive (https://adc.arm.gov/discovery/) shortly after data collection. Data collected by ARM guest instruments requires delivery to the archive within six months of the end of the deployment. ARM Value-added product availability varies depending on the complexity and the maturity of the product development activities. Data collected by other agencies will be subject to the data sharing policies of each agency.

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| Apr 2020 | TRACER Science and Logistics Planning Meeting |
| Jun 2020 | TRACER forecasting exercise |
| Oct 2021 | TRACER campaign begins |
| Jun 2022 | TRACER IOP begins |
| Jun 2021 | NSF ESCAPE Project begins |
| Jul 2021 | NSF ESCAPE Project Ends |
| Sep 2022 | TRACER IOP ends |
| Sep 2022 | TRACER campaign ends |

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