DOE/SC-ARM-15-062

Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems (HI-SCALE) Science Plan

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Summary

Cumulus convection is an important component in the atmospheric radiation budget and hydrologic cycle over the Southern Great Plains and over many regions of the world, particularly during the summertime growing season when intense turbulence induced by surface radiation couples the land surface to clouds. Current convective cloud parameterizations contain uncertainties resulting in part from insufficient coincident data that couples cloud macrophysical and microphysical properties to inhomogeneities in boundary layer and aerosol properties. The Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems (HI-SCALE) campaign is designed to provide a detailed set of measurements that are needed to obtain a more complete understanding of the life cycle of shallow clouds by coupling cloud macrophysical and microphysical properties to land surface properties, ecosystems, and aerosols. HI-SCALE consists of 2, 4-week intensive observational periods, one in the spring and the other in the late summer, to take advantage of different stages and distribution of “greenness” for various types of vegetation in the vicinity of the Atmospheric Radiation and Measurement (ARM) Climate Research Facility’s Southern Great Plains (SGP) site as well as aerosol properties that vary during the growing season. Most of the proposed instrumentation will be deployed on the ARM Aerial Facility (AAF) Gulfstream 1 (G-1) aircraft, including those that measure atmospheric turbulence, cloud water content and drop size distributions, aerosol precursor gases, aerosol chemical composition and size distributions, and cloud condensation nuclei concentrations. Routine ARM aerosol measurements made at the surface will be supplemented with aerosol microphysical properties measurements. The G-1 aircraft will complete transects over the SGP Central Facility at multiple altitudes within the boundary layer, within clouds, and above clouds.

The extensive measurements collected during the campaign will be coupled with routine ARM SGP ‘megasite’ measurements as well as large eddy simulation (LES), cloud resolving, and cloud-system resolving models. Through integrated analyses and modeling studies, scientists will be able to quantify the influence of inhomogeneities in land use, vegetation, soil moisture, convective eddies, and aerosol properties on the evolution of shallow clouds. This includes the feedbacks of clouds on the downwelling radiation reaching the surface and associated changes in the surface heat, moisture, and momentum fluxes and on aerosol photochemical processes. Findings from the data analyses and modeling studies will be used to develop improved parameterizations for the next generation of climate models that are expected to have grid spacing of ~10 km. In addition, the aircraft and surface measurements will provide critical in situ measurements of the boundary layer, cloud microphysics and dynamics, and aerosol properties that can be used to evaluate the new routine LES modeling activity at the SGP site as well as various current and new ARM retrievals.

Acronyms and Abbreviations

AAF	ARM Aerial Facility
ACAPEX	ARM Cloud Aerosol Precipitation Experiment
ACME	Accelerated Climate Modeling for Energy
ACSM	Aerosol Chemical Speciation Monitor
AERI	Atmospheric Emitted Radiance Interferometer
ARM	Atmospheric Radiation Measurement
ASL	atmospheric surface layer
ASR	Atmospheric System Research
CAM	Community Atmosphere Model
CAM5	CAM version 5
CARES	Carbonaceous Aerosol and Radiative Effects Study
CCN	cloud condensation nuclei
CESD	Climate and Environmental Sciences Division
CHAPS	Cumulus Humulis Aerosol Processing Study
CIMS	Chemical Ionization Mass Spectrometer
CLASIC	Cloud and Land Surface Interaction Campaign
CLM	Community Land Model
CLUBB	Cloud Layers Unified by Binormals
CO	carbon monoxide
CPC	Condensation Particle Counter
CSAPR	C-Band Scanning ARM Precipitation Radar
CSLAEX	Cross-Scale-Land-Atmosphere Experiment
CVI	Counter-flow Virtual Impactor
DOE	U.S. Department of Energy
EBBR	Energy Balance Bowen Ratio
EMSL	Environmental Molecular Science Laboratory
EPA	Environmental Protection Agency
FIMS	Fast Integrated Mobility Spectrometer
G-1	Gulfstream-1
GIS	graphical information system
HI-SCALE	Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems
HR-ToF-AMS	High Resolution Time-of-Flight Aerosol Mass Spectrometer
HRRR	High Resolution Rapid Refresh model
IOP	intensive observational period
LAI	leaf area index
LES	large-eddy simulation

LLNL	Lawrence Livermore National Laboratory
MAM	Modal Aerosol Module for CAM5
MC3E	Mid-latitude Continental Convective Cloud Experiment
miniSPLAT	miniaturized Single Particle Laser Ablation Time-of-flight
MOSAIC	Model for Simulating Aerosol Interactions and Chemistry
NASA	National Aeronautics and Space Administration
NDVI	normalized difference vegetation index
NO	nitrogen oxide
NO_2	nitrogen dioxide
NOAA	National Oceanic and Atmospheric Administration
NPFS	New Particle Formation Study
OM	organic matter
PCASP	Passive Cavity Aerosol Spectrometer
PECAN	Plains Elevated Convection at Night
PDF	probability density function
PM	particulate matter
PM2.5	particulate matter smaller than 2.5 microns
PM10	particulate matter smaller than 10 microns
PMF	Positive Matrix Factorization
RACORO	Routine ARM Aerial Facility Clouds with low optical depths Optical Radiative Observations
SACR	Scanning ARM Cloud Radar
SAS	Southeast Aerosol Study
SGP	Southern Great Plains
SO_2	sulfur dioxide
SOA	secondary organic aerosol
SPLAT	Single Particle Laser Ablation Time-of-flight
SWATS	Soil Water and Temperature Profiling System
TCAP	Two-Column Aerosol Project
UCPC	Ultrafine Condensation Particle Counter
UHSAS	Ultra-high-sensitivity Aerosol Spectrometer
VAP	value-added product
VBS	volatility basis set
VOC	volatile organic compound
WRF	Weather Research and Forecasting model
WRF-Chem	Weather Research and Forecasting model with chemistry
XSAPR	X-Band and Scanning ARM Precipitation Radar

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1.0 Background

Shallow convective clouds are quite common, occurring over many areas of the world, and are an important component in the atmospheric radiation budget. Over the Southern Great Plains, shallow convective clouds frequently occur during the summertime growing season when intense turbulence induced by surface radiation couples the land surface to clouds. Shallow cumulus clouds at the Atmospheric Radiation Measurement (ARM) Climate Research Facility's Southern Great Plains (SGP) site have an average surface shortwave radiative forcing of −45.5 W m^{-2} (Berg et al. 2011a) and mean spatial scale of ~1.0 km (Berg and Kassianov 2008). This means they are an important part of the radiation budget, yet they occur at the sub-grid scale for all climate models and must be represented by parameterizations.

The Southern Great Plains is also a 'hotspot' of land-atmosphere interactions. Several studies have examined the magnitude of the coupling between surface processes and precipitation in climate models (e.g., Charney et al. 1977; Henderson-Sellers and Gornitz 1984; Koster et al 2002, 2004, 2006; Dirmeyer et al. 2006; Findell et al. 2011). Using 12 global climate model simulations, Koster et al. (2006), showed that the greatest magnitude in the summer coupling between land surface and precipitation can be found over a limited number of areas, including the SGP, as shown in Figure 1. The location of the ARM SGP site within the 'hotspot' over North America and its long-term observations make that site ideal for a detailed study of land-atmosphere-cloud interactions, such as the Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems (HI-SCALE) field campaign.

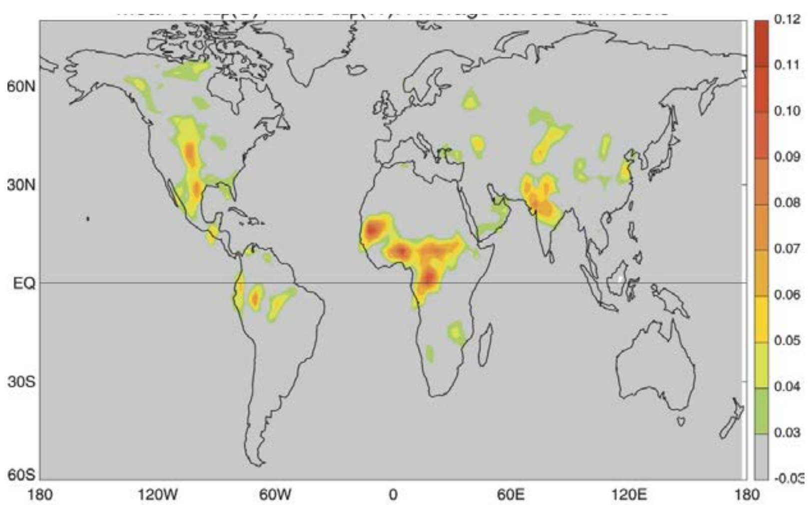

Figure 1. Average relative coupling of land-surface processes to precipitation for a suite of 12 global climate models (after Koster et al. 2006).

Regional and global climate models cannot explicitly resolve shallow and deep convective clouds; consequently, parameterizations are required to represent the vertical mixing of atmospheric constituents, precipitation, and radiative effects associated with those clouds. In addition, the spatial variability of land-surface and subsurface states and fluxes (e.g., soil moisture, vegetation distribution and phenology) within climate model grid cells and their effects on boundary layer mixing and clouds are often neglected or treated in a simplistic way (Essery et al. 2003; Manrique-Suñén et al. 2013; Rieck et al. 2014). While the spatial resolution used by the next generation of climate models will increase significantly over the next 5 to 10 years so that horizontal grid spacings of ~10 km will become common, this resolution will still be insufficient to represent shallow convective clouds and many of the processes that affect their initiation and lifetime. Even current high-resolution weather forecast and cloud-resolving models do not fully resolve shallow convective clouds (e.g. Berg et al. 2013). Current shallow and deep convective cloud parameterizations contain uncertainties resulting from insufficient coincident data that couples cloud macrophysical and microphysical properties to inhomogeneity in the surface layer, boundary layer, and aerosol properties. Coincident data are a key factor needed to achieve a more holistic understanding of the life cycle of shallow convective clouds and to develop improved parameterizations for climate models.

Long-term and short-term measurements collected in the vicinity of the ARM SGP site since 1992 have already provided valuable information needed to improve the understanding of specific processes associated with shallow convective clouds, land-atmosphere interactions, and aerosols. Several notable short-term field campaigns were conducted in the past decade.

The 2007 Cloud and Land Surface Interaction Campaign (CLASIC) was a cross-disciplinary campaign in which numerous aircraft flights were conducted in areas distant from the SGP Central Facility in order to advance the understanding of how land surface processes influence cumulus convection. The campaign data facilitated the development of new satellite retrievals to characterize variations in albedo, land cover, and biophysical quantities (Roman et al. 2011; 2013) as well as the retrieval of aerosol optical depth in the vicinity of broken clouds (Kassianov et al. 2010). Bindlish et al. (2009) describe the deployment of an airborne passive/active L-band sensor that quantified soil moisture variations over the site that were also compared with in situ measurements. Brunsell et al. (2011) performed large-eddy simulations (LES) that included heterogeneous surface conditions for select periods to quantify how changes in net radiation affected turbulent transport near the surface. However, 2007 was the wettest summer on record for Oklahoma (145 cm), leading to all of the soils in the region being saturated (or nearly saturated) so that surface fluxes did not vary significantly across the region. A parallel campaign, the 2007 Cumulus Humulis Aerosol Processing Study (CHAPS), was designed to measure the properties of shallow convective clouds as well as interstitial and cloud-borne aerosol using the G-1 aircraft (Berg et al. 2009). Berg et al. (2011b) used the aircraft measurements of cloud and aerosol properties to show that even moderately sized cities, such as Oklahoma City, can have a measureable impact on the optical properties of shallow clouds (i.e., the first aerosol indirect effect). Data from CHAPS have also been used to develop new parameterizations of shallow convective clouds (Berg et al. 2013) that improve the simulation of downwelling shortwave radiation as well as treating the interaction of aerosols with sub-grid scale clouds (Berg et al. 2015a). Shrivastava et al. (2013a) also used CHAPS data to evaluate high-resolution simulations that treat aqueous chemistry in clouds.

Two years later, the 2009 Routine ARM Aerial Facility (AAF) Clouds with Low Optical Depths Optical Radiative Observations (RACORO) (Vogelmann et al. 2012) campaign conducted routine flights with a Twin Otter aircraft to obtain measurements below, within, and above liquid shallow clouds in the vicinity of the SGP. Lu et al. (2014) used the aircraft data to show that models need to consider the averaging time scale in representing entrainment-mixing processes in models. RACORO aircraft data were used by Turner et al. (2014) to evaluate turbulence profiles of water vapor mixing ratio variance and skewness from the SGP Raman lidar and demonstrated that the lidar provided better resolution and interpretation of turbulence profiles in the interfacial layer that is important for process studies and model evaluation. Lu et al. (2012a) used the aircraft data to show that with increasing vertical velocity, the droplet number concentration increases while the relative dispersion decreases, which is the opposite of the effect associated with changes in aerosol loading. This finding poses a challenge for separating aerosol indirect effects from dynamical effects. For the first time, Lu et al. (2012b) calculated the probability density function of entrainment as a function of distance from the edge of the cloud using the aircraft data. Lu et al. (2013) then showed that cloud microphysical quantities exhibited strong relationships with entrainment rate, suggesting that the dominance of homogeneous entrainment mixing does not favor the formation of large droplets and the initiation of warm rain in shallow convective clouds.

The Mid-latitude Continental Convective Cloud Experiment (MC3E) conducted in the spring of 2011 was designed to study mature deep convection and the diurnal evolution of deep convection (Jensen et al. 2015). Heat and moisture budgets over the SGP region based on the enhanced sounding array during that campaign were used by Xie et al. (2014) to study the processes associated with the interaction of cumulus convection and the large-scale environment. Data from the new radar systems deployed for the first time during MC3E have been described in Heymsfield et al. (2013), Giangrande et al. (2014), and Battaglia et al. (2014). The campaign measurements are now being used by in a number of ongoing modeling studies, including a microphysics comparison study being conducted by the Atmospheric System Research (ASR) Cloud-Aerosol-Precipitation Interaction working group. Tao et al. (2013) was the first modeling study of deep convection observed during MC3E. They found that their model overestimated rainfall for light precipitation events, that cold pools dynamics were an important physical process, and that larger-scale terrain effects are important during the initial stages of one propagating mesoscale convective system.

The 2013 New Particle Formation Study (NPFS) obtained a wealth of information on the size distribution and composition of newly formed particles and their growth at the SGP site using a Thermal Desorption Chemical Ionization Mass Spectrometer (CIMS) (Smith et al. 2008). The sampling during April and May was mostly surface-based, although profiles were obtained via tethersondes on 3 days. An analysis of previous SGP Central Facility measurements suggests that new particle formation events peak during the spring and fall, with fewer events during the summer. The growth of these ultrafine particles to relevant cloud condensation nuclei (CCN) sizes is likely controlled by secondary organic aerosol (SOA) processes. Since the campaign is relatively recent, papers describing the findings have not yet been published.

In addition to these past campaigns, there are two upcoming campaigns related to the objectives of HI-SCALE. The first is a campaign at the SGP site this June through August 2015 that will have 12 1-day intensive observational periods (IOPs) in which 14 radiosondes are launched each day. The goals of this study are to address spatial variability of meteorology over the SGP site and demonstrate how ARM could better observe land-atmosphere coupling to help evaluate and improve climate models. The second is the Plains Elevated Convection at Night (PECAN) campaign sponsored by the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the U.S. Department of Energy (DOE) to be conducted between June and July of 2015. The objective of this campaign is to improve the understanding and simulation of the processes that initiate and maintain convection and convective precipitation at night over the Great Plains, which is currently poorly represented by climate models. A high temporal resolution supplemental sounding array will be deployed over a large region encompassing Oklahoma, Kansas, and Nebraska. When this information is coupled with operational ARM data, it will provide a data set that augments MC3E as a resource to study the diurnal evolution of deep convection.

Despite the advances made by CLASIC, CHAPS, RACORO, MC3E, and NPFS, none of them provided sufficient information to obtain a holistic understanding of the various processes influencing the evolution of shallow clouds. Instead, each campaign targeted specific processes that affect the life cycle of shallow convective clouds in the vicinity of the SGP site. As stated previously, 2007 was the wettest summer on record, so that during CLASIC the soil moisture variations in the vicinity of the SGP site were small. Much of the aircraft sampling during CHAPS was not conducted directly over the SGP site and therefore could not be tied to the SGP measurements of cloud or aerosol properties. Nor were the aircraft flights designed to understand how variations in surface fluxes affect clouds. While some aerosol measurements were made during RACORO, information on aerosol composition and the full range of the aerosol size distribution needed to fully understand the evolution of the aerosol life cycle in the vicinity of the SGP site was not obtained. The focus of MC3E was on deep convection, so there was little focus on boundary layer processes, shallow clouds and their transitions to deep convection, and coupling with aerosols. The impact of nucleation and the subsequent aerosol growth was not linked with coincident measurements of aerosols and CCN near the cloud base during NPFS, nor were there in situ cloud property measurements. In addition, coupling the aircraft measurements with the new ‘megasite’ data such as the dense network of vertically pointing, remote sensing instruments and new scanning radars and Doppler lidar (unavailable to most previous campaigns) provides an unprecedented opportunity to advance our understanding of how variability in boundary layer mixing, aerosols, and land-atmosphere interactions controls the initiation, properties, and evolution of shallow clouds.

Some of the remaining scientific issues associated with shallow convective clouds include the:

1) effects of heterogeneous land-use, vegetation, and soil moisture conditions on boundary layer mixing and consequently cloud formation, initiation of precipitation (especially drizzle), and transition from shallow-to-deep convection;
2) role of cloud population (size, organization) and entrainment on precipitation onset and cloud lifetime under different aerosol environments;
3) effects of aerosol size, number concentration, composition, and mixing state on CCN number;
4) importance of new particle formation to adequately represent the growth of the aerosol size distribution and its impact on CCN; and
5) relative effects of biomass burning, biogenic-anthropogenic aerosol interactions, and atmospheric aging on CCN.

These processes will also be influenced by the larger-scale ambient meteorology that transports atmospheric constituents into the region of interest and modulates local thermodynamic forcing.

2.0 Scientific Objectives of HI-SCALE

The first scientific objective of the campaign is to obtain a holistic understanding of the life cycle of shallow clouds by coupling cloud macrophysical and microphysical properties to land surface properties, ecosystems, and aerosols. This includes quantifying the influence of inhomogeneities in land use, vegetation, soil moisture, convective eddies, and aerosol properties (size distribution, composition, mixing state) on the evolution of shallow clouds as well as the feedbacks of cloud radiative effects on the surface heat, moisture, and momentum fluxes and on aerosol photochemical processes via changes in the downwelling radiation reaching the surface.

To achieve this objective, coincident measurements of meteorological, cloud, and aerosol properties will be collected by the AAF Gulfstream 1 (G-1) aircraft platform over the SGP site. Analysis and modeling studies will couple the in situ measurements collected by the G-1 aircraft during two IOPs with measurements from surface-based instrumentation, including both routine data from the extensive ground-based instrumentation over the SGP 'megasite' and IOP data obtained from additional instrumentation co-located at the SGP Central Facility.

By 2016, the reconfiguration underway at the SGP 'megasite' will provide numerous surface in situ measurements as well as vertically pointing and scanning remote sensing instruments to obtain information on the meteorological state and cloud properties. For example, there will be several surface sites that measure soil moisture, downwelling shortwave radiation, and fluxes of momentum, heat, and moisture. Still, these measurements may be insufficient to fully characterize the true spatial variability and its influence on clouds as they pass over the SGP site. We also anticipate that key information will be missing aloft on the spatial variability of temperature, humidity, winds, cloud microphysics and dynamics, and aerosol properties, as well as changes in turbulent fluxes with height from the surface to cloud base. Additional data are therefore needed to fully resolve the initiation and life cycle of shallow clouds and the transition to precipitating convection. The SGP Central Facility has a long history of a few routine measurements of aerosol properties at the surface (e.g., Sheridan et al. 2001), but information on aerosol properties aloft is limited to backscatter profiles from lidars or in situ sampling of aerosol optical properties from routine research flights during cloud-free conditions using the Cessna 206 (Andrews et al. 2011a,b) that are insufficient to characterize aerosol mass, composition, size distribution, and mixing state. While ARM produces a value-added product (VAP) that estimates CCN at cloud base, these estimates may not be representative over the site and need to be validated with in situ measurements aloft to fully understand how aerosol size, composition, and mixing state influences CCN concentration, cloud formation, and cloud properties.

Over the next two years ARM will also be developing the capability to perform routine high-resolution simulations over the SGP site. When coupled with the dense new 'megasite' measurements after the reconfiguration, analyses of these simulations will provide information that can lead to a better understanding of the processes affecting the life cycle of shallow clouds. Therefore, the second objective of the proposed IOP aircraft and surface instrumentation campaign is *to provide critical* in situ *measurements of the boundary layer, cloud microphysics and dynamics, and aerosol properties that can be used to evaluate both the high-resolution simulations and various current and new ARM retrievals.* For example, there are numerous existing measurements that can be used to initialize and evaluate the meteorology of the high-resolution model, but there will be no routine measurements of interstitial and cloud droplet residuals (i.e., cloud-borne aerosols) that can be used to initialize aerosol profiles and understand how cloud-aerosol interactions should be treated in models.

3.0 Observation Program

3.1 Measurement Strategy

The campaign will consist of two, four-week sampling periods, one in the spring (April 24 to May 21) and one in the late summer (August 28 to September 24) to take advantage of different stages and distribution of "greenness" for cultivated crops, pasture, herbaceous, and forest vegetation types as well as soil moisture content in the vicinity of the SGP. The variability in land-cover properties is captured by the seasonal variation in Leaf Area Index (LAI) shown in Figure 2. Sampling during the spring will provide data needed to understand how seasonal and heterogeneity-driven variations in

evapotranspiration, sensible heat, and skin temperature associated with maturing winter wheat and increasing LAI of various vegetation types affect cloud initiation and maintenance. For the spring period, we expect peak aerosol mass loadings associated with biomass burning and/or anthropogenic sources based on analyses of mass spectra from the Aerosol Chemical Speciation Monitor (ACSM) at the SGP site (Parworth et al. 2015). During the late summer the LAI of pasture, herbaceous, and forest vegetation types decreases and subsequently produces less transpiration. At this time, biogenic sources of aerosol become relatively more important and biomass-burning aerosol sources are small (Parworth et al. 2015). Moreover, precipitation initiation from locally triggered convective clouds also peaks during late summer. As in all campaigns, there will be episodic events that may not influence the SGP every year, but will be treated as opportunities if they do occur. For example, smoke plumes from large biomass burning events from Central America can be transported over the central U.S. under certain synoptic conditions (e.g., Wang and Christopher 2006; Wang et al. 2009). Depending on the altitude of these layers of smoke, cloud development over the SGP site could be influenced by aerosol direct, semi-direct, and indirect effects.

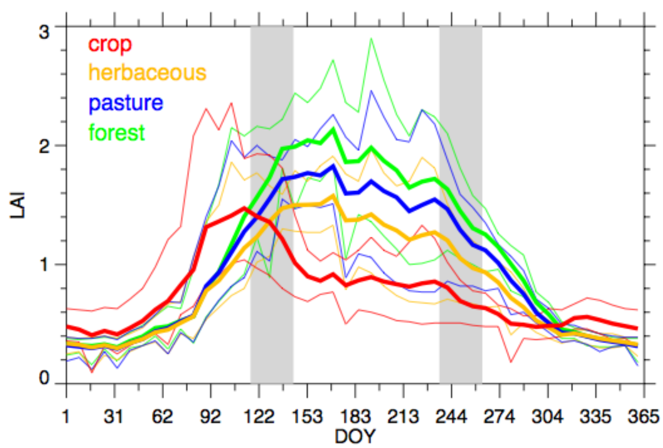

Figure 2. Average (thick lines) and range (thin lines) Leaf Area Index (LAI) near the SGP site between 2006 and 2013 Shading denotes proposed G-1 sampling period.

Therefore, sampling in two seasons will provide information on how changes in land-atmosphere interactions and aerosol type influence shallow convective clouds. In addition, there is generally a west-to-east gradient in soil moisture throughout the year, providing a regional background on which local evapotranspiration gradient variations are superimposed.

Potential flight paths for the G-1 are shown in Figures 3, 4, and 5. We plan to fly several level stacked legs near the surface, within the boundary layer, just below cloud base, within the clouds, and just above the clouds (Figure 3). Each leg will be ~5 minutes in duration to obtain sufficient statistics. Given a ~100 m s^{-1} flight speed, the total distance covered in 5 min is ~30 km. We anticipate 4 to 5 stacked legs in a column would require 30 to 35 minutes as ~2 minutes is needed to turn around between legs. For sampling strategy ‘A’ (Figure 4), two long transects at two altitudes, one within and one above the boundary layer, would be performed prior to main sampling over the SGP site to characterize the regional variability in meteorological, cloud, and aerosol properties. One stacked column would then be conducted along the ambient wind direction, following convective eddies, and passing directly over the SGP Central Facility. Then, a stacked column would sample across the wind direction, followed by a subsequent stacked column along the ambient wind direction and over the same path as the first stacked column. Sampling strategy 'B' (Figure 5) is similar except that it provides more spatial coverage over the SGP site and will intersect a larger region of the volume sampled by scanning radars. However, flying over a larger area requires more time; therefore, the number of stacked altitude legs needs to be reduced from 5 to 3. The advantage of flying over the Central Facility and other Extended Facilities for both sampling strategies is to permit coupling of surface-based and aircraft measurements in deriving profiles of turbulence fluxes and other quantities.

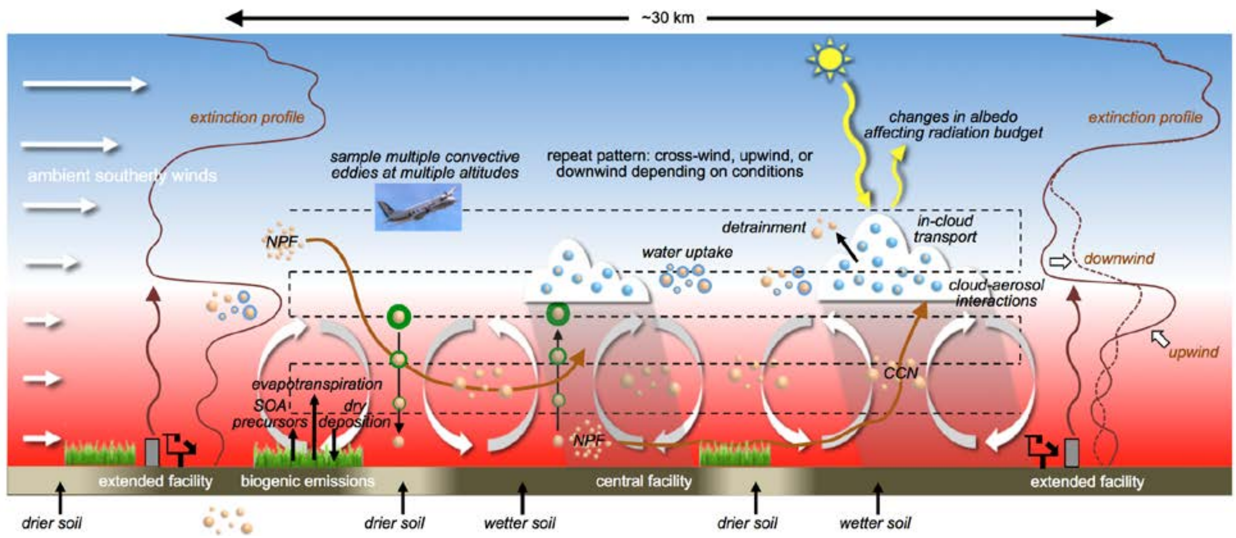

Figure 3. Schematic diagram for the stacked G-1 flight pattern in the vicinity of the ARM Central Facility along with atmospheric processes to be studied.

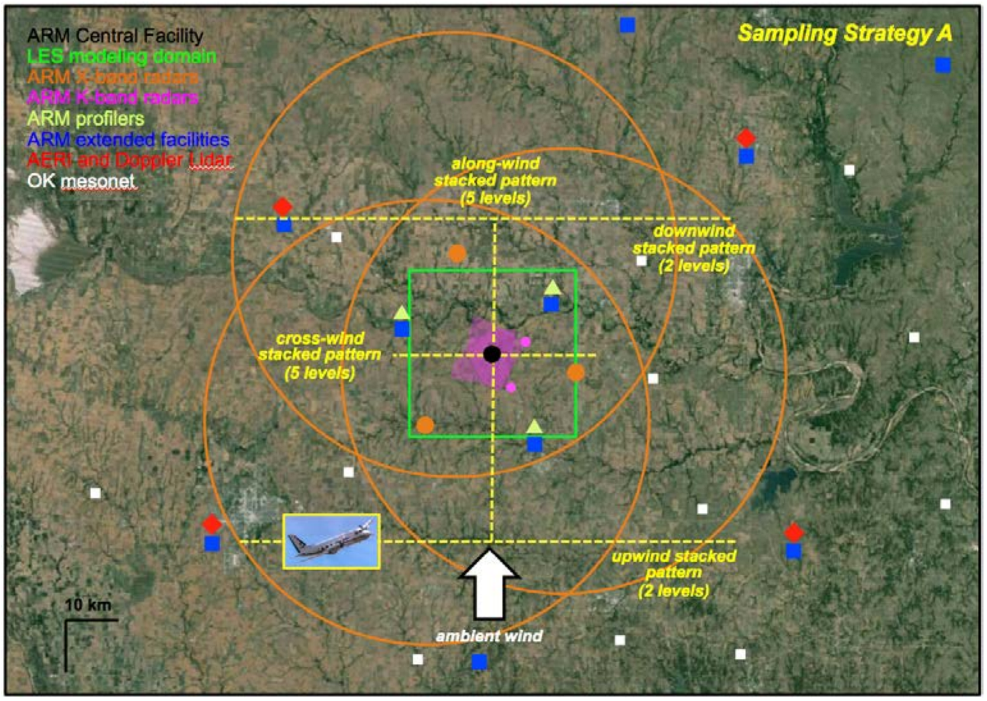

Figure 4. Locations of meteorological sampling in the vicinity of the ARM SGP site along with the proposed G-1 flight pattern for "sampling strategy A." The flight pattern will be rotated depending on the ambient wind direction.

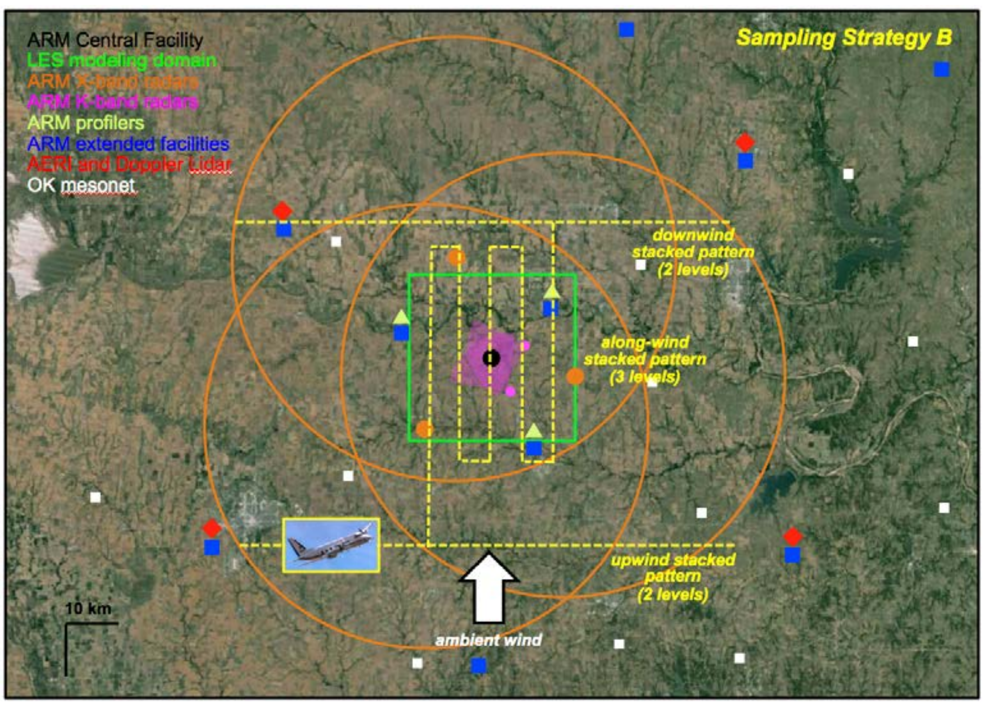

Figure 5. Same as Figure 4, except for "sampling strategy B."

On some days, two flights per day may be conducted: a morning flight to sample shallow clouds shortly after formation and a repetition during the afternoon as the cloud population matures and as cloud droplet processing by aerosols progresses. The morning flights are also crucial for observing the growth of the boundary layer and the mixing of aerosol between the surface and the free troposphere.

Sampling strategy ‘A’ has the advantage of capturing both temporal and spatial variability of meteorological, cloud, and aerosol properties within the boundary layer, just below cloud base, within clouds, and in the free troposphere just above cloud tops. By focusing on sampling along the wind direction the aircraft will sample the evolution of convective eddies and aerosols within those eddies as clouds are advected over the SGP site. However, sampling strategy ‘B’ covers a larger fraction of the anticipated ARM routine LES modeling domain. The broader area covered aligns well with the sampling by the scanning radars and will enable us to collect robust statistics to identify clouds susceptible to spatial forcing from variable vegetation and soil moisture distributions. Both sampling strategies have the G-1 aircraft flying over the Central Facility multiple times. The flight plans will be adjusted to fly over the Extended Facilities (depending on their location in 2016) that will also depend on the ambient wind direction and flight duration. We plan to conduct both sampling strategies during each IOP, but the number of flights for each sampling strategy will depend on the observed meteorological conditions.

We anticipate coordinating our flights with Scanning ARM Cloud Radar (SACR) operations in consultation with the radar mentors to optimize scanning strategies that target shallow cumulus clouds. An example of shallow clouds sampled by SACR is shown in Figure 6. Macrophysical properties such as the cloud chord length, cloud-top height, cloud lifetime, and their contribution to cloud fraction will be characterized by SACR. Coordinating the G-1 flights over the SGP site with the radar will allow collocated measurements of turbulent mixing and entrainment rates from cloud base to cloud top. We plan to use the X-Band and Scanning ARM Precipitation Radar (XSAPR) and C-Band Scanning ARM Precipitation Radar (CSAPR) to identify initiation of precipitating convective cells and trace those cells back to shallow cloud fields to examine changes in cloud size, depth, and spacing before precipitation initiation. This data will be coupled with aircraft-measured profiles of moisture, turbulence, and entrainment rate. Differences between low and high aerosol loading periods will also be determined. Prior to the campaign, we plan to use LES results for select cases to refine the flight patterns and determine the best sampling strategy to generate statistics on convective eddies, clouds, and length of time sampling within clouds. We will also consult with the AAF staff regarding the flight paths, weighing the science objectives with the logistical considerations.

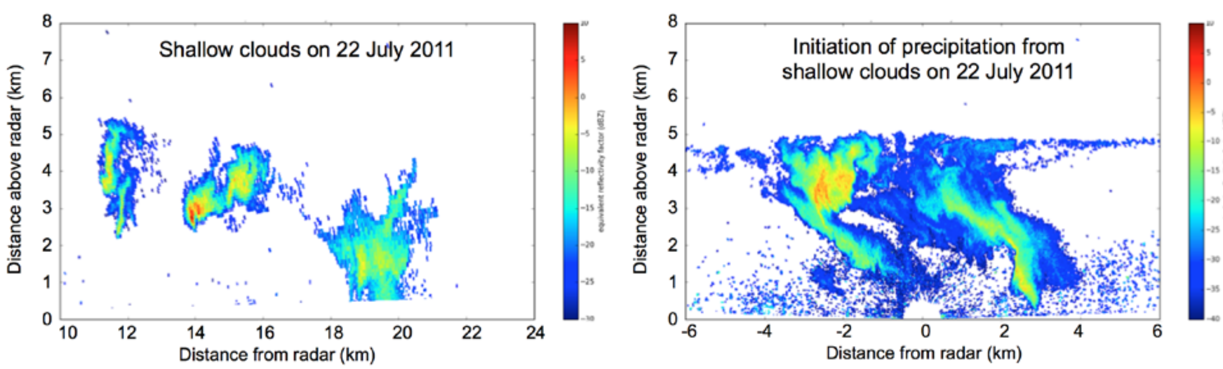

Figure 6. Example scans from SACR at the SGP site on 22 July 2011.

An example of the frequency of the G-1 intersecting shallow clouds is depicted in Figure 7 in which three flights from the 2007 CHAPS campaign are shown, with varying amounts of clouds. The flight legs during CHAPS were approximately twice as long as the ones planned for HI-SCALE, so that the same population of clouds can be sampled more than once and aircraft data can be coupled with routine in situ and remote sensing measurements of meteorology, clouds, and aerosols over the SGP site. Figure 7 illustrates the importance of sampling quantities at as high a frequency as possible since the aircraft can quickly pass through small clouds. While the sampling rate for most of the G-1 meteorological, cloud, trace gas, and aerosol size and number instruments is ~1 s, some of the proposed aerosol mass spectrometer measurements collect data at ~10 s intervals. Nevertheless, sufficient in-cloud statistics of aerosol data were obtained during CHAPS due in part to the application of the counterflow virtual impactor inlet, and we are confident that the slower sampling rate will not hinder subsequent analyses that investigate cloud-aerosol interactions.

In addition to cloud variability, the large variability in vegetation type and "greenness" in the vicinity of the SGP site as shown in Figures 4 and 5 is also important. For subsequent analyses of the aircraft data described in Section 4, we will obtain high-resolution vegetation data sets in the region that will vary between the spring and late summer sampling periods due to differing growth rates of various crops. Alice Ciallela (Brookhaven National Laboratory) has an archive of various data sets, some of which are graphical information system (GIS)-based, that can serve as a starting point for our analyses that will be supplemented with period-specific satellite information and data derived from G-1 measurements. An example of a 1-m resolution land cover map is shown in Figure 8. Downward-looking, multi-filter radiometer measurements on the G-1 will also be used to quantify variations in key parameters such as the normalized difference vegetation index (NDVI), revealing variations in vegetation similar to those shown in Figure 8. We will also use soil moisture data sets derived from satellites (Soil Moisture and Ocean Salinity) and neural-network retrieval of soil moisture using a synergy of sensors provided by P. Gentine (Kolassa et al. 2015) as part of his DOE Early Career project. These soil moisture data sets will be compared with the three types of in situ soil moisture measurements (SWATS, EBBR, and Oklahoma mesonet) collected at several sites in the vicinity of the Central Facility as well as across Oklahoma.

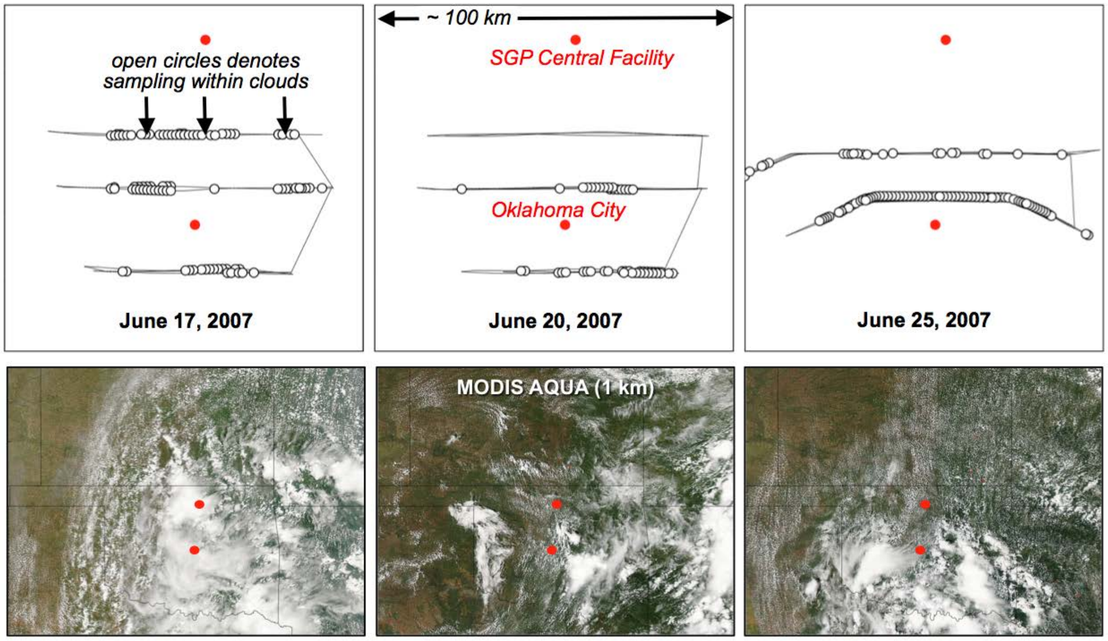

Figure 7. Locations where in situ measurements of shallow cumulus clouds were made on three days during the 2007 CHAPS campaign (top panels) along with MODIS satellite images of cloudiness over Oklahoma during each afternoon.

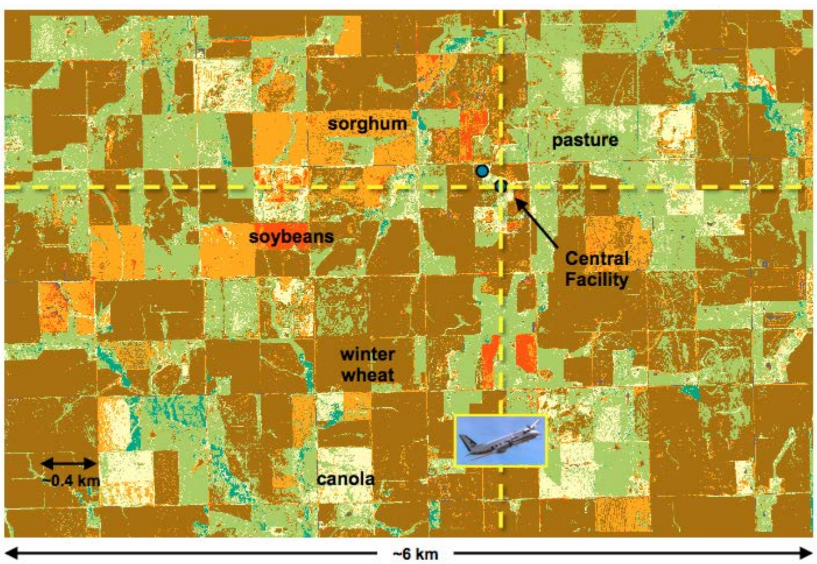

Figure 8. 1-m resolution land cover map in the vicinity of the SGP depicting various crops that will lead to differences in LAI and surface albedo.

Since the SGP site is in a rural location, it is often thought of as a “clean” site in terms of aerosol concentrations. However, this is not always the case. As described by Parworth et al. (2015), the monthly averaged mass loadings of non-refractory aerosol from the ACSM instrument vary between 2–3 mg m^{-3} during the late fall and early winter, 10–14 mg m^{-3} during the spring, and 4–8 mg m^{-3} during the summer, which is consistent with mass loading observed in other areas of the globe. Biomass burning usually contributes to the highest aerosol loading observed, especially during spring when there are prescribed agriculture burns in the region. Organic matter (OM) is the largest fraction of aerosol composition in all months except January and February when cold temperatures favor nitrate formation. Figure 9 uses the Weather Research and Forecasting with chemistry (WRF-Chem) model to show that OM in near the SGP site is likely a combination of biogenic and anthropogenic sources, depending on the ambient wind direction and other meteorological factors (temperature, humidity, cloudiness) that control SOA. While isoprene emission rates are low over the SGP site, forested regions to the east and south do emit significant amounts of isoprene so that SOA from that source can often be transported over the SGP site. In addition, SOA from anthropogenic sources can be transported over the SGP site. Even though Oklahoma City is a "moderately sized" city, the emissions can still produce noticeable plumes of OM and other aerosols many kilometers downwind. CHAPS aircraft data did show easily identifiable urban plumes in the east/west transects (Berg et al. 2009, 2011b; Shrivastava et al. 2013a) as well as a west-to-east gradient in isoprene consistent with biogenic emission sources (Figure 9). Analyses that connect aerosol composition (organics that are more hydrophobic with $0.01 < k < 0.5$ versus inorganics that are more hydrophilic with $0.5 < k < 1.4$; Petters and Kreidenweiss 2007) and observed CCN at the SGP surface site have yet to be performed. More importantly, analyses at cloud base need to be performed since aerosols at that altitude may differ significantly from those at the ground.

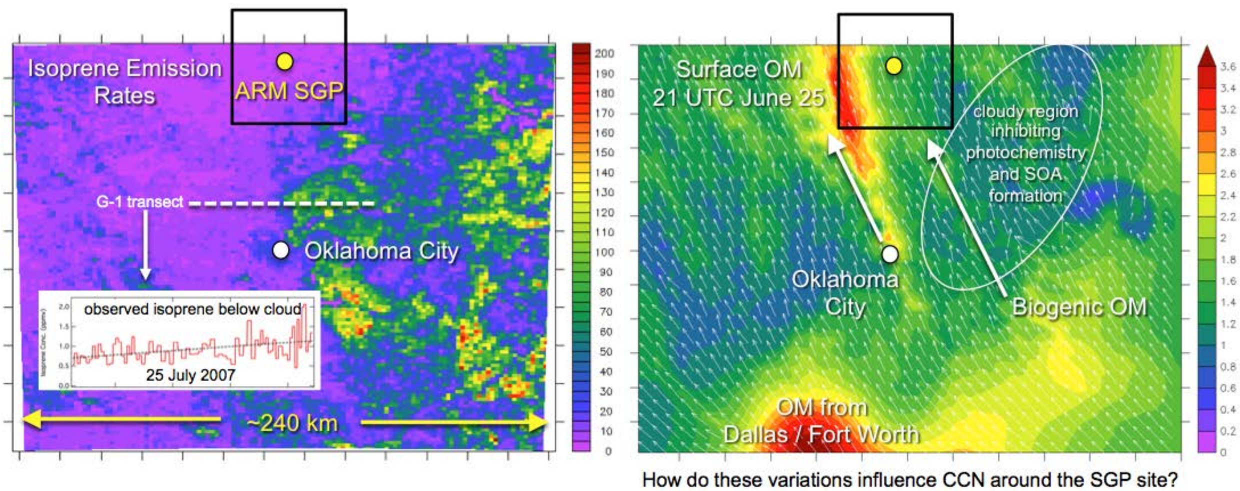

Figure 9. Isoprene emission rates obtained from the MEGAN model (left) and WRF-Chem simulation of organic matter (OM) during CHAPS on June 25 (right) using a grid spacing of 2 km. Left panel includes aircraft measurements of isoprene below clouds along one transect. Black box denotes the likely ARM LES modeling domain.

3.2 Aircraft Instrumentation

The G-1 will provide the in situ measurements needed to better understand how boundary layer processes and cloud-aerosol interactions affect the evolution of shallow clouds (see Table 1). This includes standard meteorological and radiation (both up and downwelling) variables, as well as measurements that will enable us to compute sensible and latent heat fluxes. Cloud probes, including CDP, 2D-S, HVPS-3, WCM (or other bulk water) instruments, are needed to characterize cloud microphysical properties. Trace gas monitors that measure carbon monoxide (CO), nitrogen oxide (NO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) concentrations will help differentiate between urban, industrial, and other air masses, while a CIMS will characterize important trace gas volatile organic compounds (VOCs) needed to quantify aerosol precursor concentrations and fluxes. To better characterize the aerosol life cycle and how aerosols affect cloud properties, a number of instruments are needed to measure aerosol number, size, and composition. The Fast Integrated Mobility Spectrometer (FIMS), Ultra-high-sensitivity Aerosol Spectrometer (UHSAS), Passive Cavity Aerosol Spectrometer (PCASP), and CAS instruments will be used to characterize size distribution from fine to coarse size particles, while two Condensation Particle Counters (CPC) (one for sizes > 1 nm and one for sizes > 10 nm) and an Ultrafine Condensation Particle Counter (UCPC) (for sizes > 3 nm) will be used to quantify total aerosol number concentration. A High-resolution, Time-of-flight Aerosol Mass Spectrometer (HR-ToF-AMS) will characterize bulk aerosol composition and size (e.g. Shilling et al., 2013), and the mini Single Particle Laser Ablation Time-of-flight (miniSPLAT) (Zelenyuk et al. 2015) will characterize the composition and size of individual aerosol particles. The Dual-Cloud-Condensation-Nuclei Counter will be used to quantify cloud condensation nuclei concentrations.

Table 1. Planned instrumentation on the G-1 aircraft.

Instrument	Measurement	Facility/Contact
Aircraft Integrated Meteorological Measurement System (AIMMS-20)	5-port air motion sensing: true air speed, altitude, angle-of-attack, side-slip, and temperature,	ARM Aerial Facility (AAF)
Gust probe	High temporal resolution wind components	AAF
Infrared thermometer	Skin temperature	AAF
MFR	Upwelling shortwave radiation global, 415, 500, 615, 673, 870 ,940,1625 nm spectral channels	AAF
SPN-1 Unshaded, Shaded	Broadband upwelling and downwelling shortwave radiation global, broadband downwelling shortwave radiation global and diffuse	AAF
CDP Cloud Droplet Probe	Size distribution, 2 – 50 microns	AAF
2-Dimensional Stereo Probe (2D-S)	Size distribution 10 to 3,000 microns	AAF
High-volume Precipitation Spectrometer Version 3 (HVPS-3)	Size distribution 400 to 50,000 microns	AAF
WCM-2000 Multi-Eeement Water Content System	Liquid, total, and ice water content	AAF
Cloud Spectrometer and Impactor (CSI)	Total water content	AAF
Trace Gas Instrument System for CO	Tracer of anthropogenic plumes, primarily mobile sources	AAF
Trace Gas Instrument System for SO_2	Tracer of anthropogenic plumes, primarily industrial sources	AAF
Trace Gas Instrument System for NO	Tracer of anthropogenic plumes, photochemical age, SOA regime	AAF
Trace Gas Instrument System for NO_2	Tracer of anthropogenic plumes, photochemical age, SOA regime	AAF
Time-of-flight Chemical Ionization Mass Spectrometer (HR-ToF-CIMS)	Volatile organic compounds (VOCs)	UW (Joel Thornton)
Fast Integrated Mobility Spectrometer (FIMS)	Aerosol size distribution (0.015 to 0.4 microns)	BNL (Jian Wang)
Ultra-high-sensitivity Aerosol Spectrometer (UHSAS)	Aerosol size distribution 0.055 to 1 microns	AAF
Passive Cavity Aerosol Spectrometer (PCASP)	Aerosol size distribution 0.1 to 3 µm	AAF
CAPS	Aerosol and cloud drop size distribution 0.5 to 50 µm	AAF
UCPC TSI 3025	Total particle concentration (> 3 nm)	AAF
CPC TSI 3010	Total particle concentration (> 10 nm)	AAF

High-resolution, time-of-flight Aerosol Mass Spectrometer (HR-ToF-AMS)	Non-refractory aerosol composition	PNNL (John Shilling)
Compact Single-particle Laser Ablation Time of flight (miniSPLAT)	Aerosol mixing state, on a real-time, particle-by-particle basis, with simultaneous measurements of aerosol size, density, shape	PNNL/EMSL (Alla Zelenyuk)
Dual-column Cloud Condensation Nuclei Counter (Dual-CCNC)	CCN concentration at two specified supersaturations	AAF
Isokinetic Inlet and Counter-flow Virtual Impactor (CVI)	Liquid water content and particle number concentration	AAF

We also plan to use both an isokinetic inlet and a counter-flow virtual impactor (CVI) inlet to sample aerosols, similar to the G-1 deployment during CHAPS, the ARM Two-Column Aerosol Project (TCAP), and the ARM Cloud Aerosol Precipitation Experiment (ACAPEX). In this way, we have tools available to determine the composition of aerosols in cloud droplet residuals sampled by the HR-ToF-AMS, miniSPLAT, and CIMS instruments when the CVI inlet is used to sample cloud drops. The combination of the CVI inlet and CIMS will provide data that will reveal aqueous chemistry of organics that can be used to better understand the budget of organic aerosols in the atmosphere and consequently its impact on CCN. The measurements of cloud-borne aerosols and chemistry are rarely made and are needed to provide data to constrain a major uncertainty in climate models.

The samples of most of the meteorological, cloud, and trace gas measurements are made at 1-s intervals. When this data are coupled with high-frequency temporal data collected by the CIMS, we will be able to compute fluxes of several VOCs, including isoprene. We will then be able to differentiate between local emissions of biogenic VOCs mixed up through the convective boundary layer (aerosols likely fresher, possibly more hydrophobic) and VOCs transported over the SGP site (aerosols more aged, and possibly more hydrophilic). An example of this technique is shown in Figure 10 for an aircraft mission in the southeastern U.S. Note that the regions of high isoprene flux are not stacked in a vertical column because the convective eddies are transported by the ambient winds and a period of time passes before the aircraft can sample the same eddy. Alex Guenther and his team are currently performing similar analyses of the G-1 measurements collected during the 2010 Carbonaceous Aerosol and Radiative Effects Study (CARES) and 2014 GoAmazon campaigns.

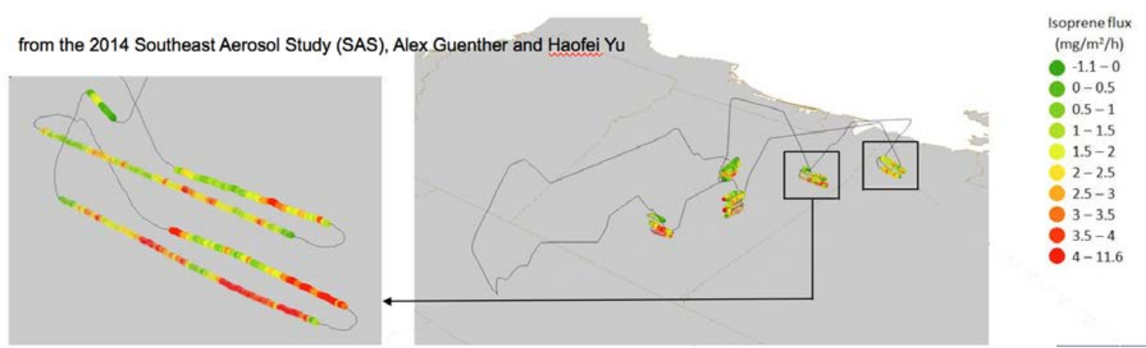

Figure 10. Isoprene fluxes computed along various aircraft flight legs using high-temporal data collected during the Southeast Aerosol Study (SAS)**.**

3.3 Supplemental Surface Instrumentation

We are planning on two additional radiosonde launches per day on G-1 flight days (for a total of six per day). The measurements at the SGP Central Facility will be supplemented with two additional instruments supported by the Environmental Molecular Science Laboratory (EMSL). Since the operational ACSM instrument at the SGP site produces data over 30-minute intervals and cannot provide information on size distribution of composition, a HR-ToF-AMS will be deployed to characterize size-resolved aerosol composition and Single Particle Laser Ablation Time-of-flight (SPLAT II) to characterize composition, size, and volatility of individual aerosol particles. By coupling the surface measurements with those collected by the G-1 during overpass periods, we will be able to characterize vertical variations of meteorological and aerosol properties within boundary layer eddies up to cloud base, connect those properties to CCN concentrations, and assess the vertical representativeness of surface measurements.

3.4 Supplemental Operational Data

In addition to the ARM operational 'megasite' and IOP data, we also plan to integrate a diverse set of operational data collected by other government agencies (NASA, NOAA, and the EPA) for our post-campaign scientific analyses. The purpose of obtaining other data types is to provide a larger-scale context for the HI-SCALE measurements. Most importantly, satellite (e.g., cloud cover) and precipitation radar data are needed to provide regional distributions of cloudiness and rain upwind and downwind of the SGP site. Meteorological analyses produced by NOAA that assimilate operational data in near-real time (e.g., High-resolution Rapid Refresh model, HRRR) are needed to understand the meteorological regimes in which the G-1 aircraft is sampling. One goal of ARM is to make some of its routine measurements available in real time by 2016 so that they can be assimilated into NOAA forecast models, thus improving the analyses in the vicinity of the SGP site. We will also use relevant point observations in the region, such as surface meteorology and soil moisture/temperature from the Oklahoma Mesosnet and EPA's monitoring data on trace gases and particulates. The network of particulate matter smaller than 10 microns (PM10) and particulate matter smaller than 2.5 microns (PM2.5) monitors in Oklahoma is shown in Figure 11. Trace gas and particulate matter (PM) speciation measurements are not necessarily co-located with PM10 and PM2.5 monitors.

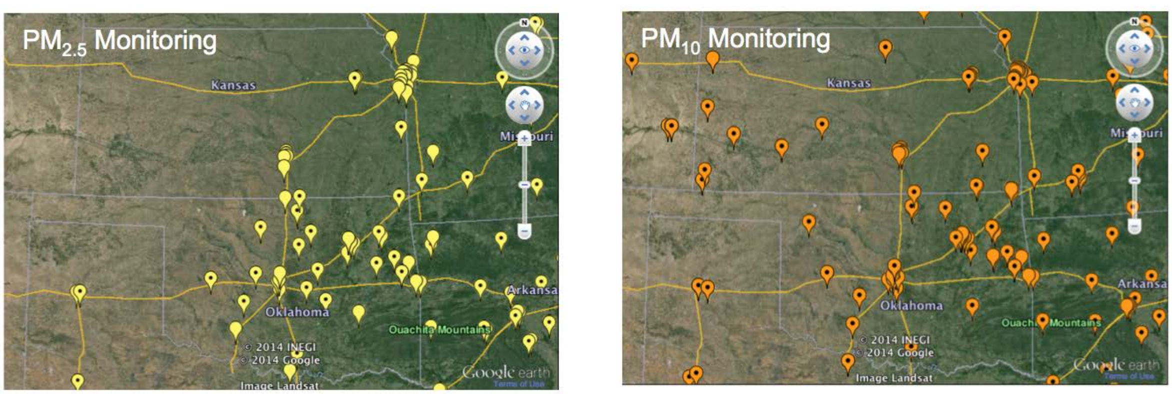

Figure 11. Locations of EPAs PM2.5 and PM10 monitors in the vicinity of the SGP site.

3.5 Synergy with ARM Megasite and Routine High-resolution Modeling

The ARM Facility is entering a new era in which its observing systems will be augmented by routine, high-resolution modeling (ARM Climate Research Facility 2014a) to enable better understanding of cloud, radiation, aerosol, and land-surface processes. This approach will facilitate the ARM's mission "to improve the understanding and representation, in climate and Earth system models, of clouds and aerosols as well as their interactions and coupling with the Earth's surface" (ARM Climate Research Facility 2014b). The new modeling capability fits into the ARM observational capabilities and is a natural extension of the 'megasite' concept for high-density observations that is currently being implemented. Measurements routinely made by ARM have high spatial and temporal resolutions that provide a unique capability for detailed study of climatically important small- and mesoscale processes. While ARM observational capabilities have been enhanced over the years, a high-resolution routine modeling component that provides a mechanism to synthesize a wide variety of atmospheric observations will enable new process-level understanding needed to accelerate DOE Climate and Environmental Sciences Division's (CESD) mission of improving global climate models (e.g., Neggers et al. 2012).

The initial focus of ARM modeling at SGP will be on shallow convective clouds, which are poorly simulated by climate models due to their small spatial scale compared to grid resolution, and because convection involves complicated interactions of microphysical and boundary layer processes. The recent report (ARM Climate Research Facility 2014a) on high-resolution modeling at the SGP site highlights several scientific challenges related to shallow convection that can be addressed. These include:

- *Biases in climate models.* A warm temperature bias over the Great Plains in climate models may be due to an underestimate of clouds and precipitation in the region, leading to surface shortwave fluxes that are too high and a deficit in soil moisture (e.g., Klein et al. 2006). The routine high-resolution modeling can contribute to eliminating this bias by providing new insights into the roles played by various processes in modifying the surface energy budget.
- *Representation of heterogeneities in land-surface effects.* Shallow convection is linked to variability in radiation, land use, and soil moisture through surface-sensible and latent heat fluxes. Agriculture around the SGP site presents an opportunity to study the impacts of spatial and seasonal variability from changes in evapotranspiration related to the growth-harvest cycle and irrigation, which are important but coarsely represented in all climate models (e.g., Qian et al. 2013).
- *New approaches to parameterizing convective clouds.* The routine nature of the simulations provides statistics needed to develop the next-generation cloud parameterizations for climate models, specifically for those requiring turbulence statistics that cannot be adequately measured (e.g., CLUBB, Cloud Layers United by Binormals). The simulations will also enable differentiating statistically significant signals from background variability for connecting land-surface conditions and clouds and for understanding aerosol impacts on clouds.

Our proposed field campaign seeks to obtain additional measurements aloft and at the surface that are needed to resolve these and other challenges regarding our understanding and model representation of shallow convective clouds. We plan to use both the 'megasite' and IOP measurements to perform a series of data analyses and modeling studies that will improve our understanding of the life cycle of shallow clouds and their transition to deep convection (described in more detail in the next section). The planned high-resolution modeling as part of our post-campaign research will leverage lessons learned from ARM's effort, but will differ significantly in terms of scientific direction and level of complexity in the treatment of ecosystems, clouds, and aerosols. For example, when simulating shallow convective clouds, we will explore how heterogeneous vegetation, soil moisture, and aerosols affect convective clouds that will not likely be included initially by ARM's high-resolution modeling effort.

We also expect the HI-SCALE measurements will be beneficial for two DOE Early Career projects: Yunyan Zhang's (Lawrence Livermore National Laboratory – LLNL) "The effect of soil moisture and surface heterogeneity on clouds and precipitation: inferences from ARM observations and large-eddy simulations" and Pierre Gentine's (Columbia University) "Cross-Scale-Land-Atmosphere Experiment (CSLAEX)." We plan to share and interpret field campaign data and coordinate our high-resolution research efforts.

4.0 Research Objectives

4.1 Scientific Questions and Hypotheses

Our hypothesis is that an approach that closely links high spatial resolution data on ecosystems, land surface properties, boundary layer mixing, and aerosols with cloud macrophysical and microphysical properties is needed to significantly advance our understanding and modeling of the initiation and maintenance of shallow clouds as well as the transition of shallow clouds to deep convection. The following science questions will guide our post-campaign research:

- *How do variations in vegetation, soil moisture, surface albedo, and downwelling radiation affect surface-sensible and latent heat fluxes and subsequently the sub-grid variability of temperature, humidity, and vertical velocity in the boundary layer? What are the relative roles of local and regional scale processes on the initiation and life cycle of shallow clouds?*
- *What is the impact of entrainment mixing at the boundary layer top on CCN concentrations? How does entrainment mixing impact cloud-aerosol interactions and vice versa?*
- *How do new particle formation, secondary organic aerosol formation, and aerosol growth contribute to CCN concentration? Do vertical variations in aerosol properties in the boundary layer contribute to vertical variation in CCN concentrations?*
- *What are the relative impacts of anthropogenic, biogenic, and biomass burning sources of aerosols from both local sources and long-range transport on cloud properties? Do variations in these aerosol sources impact cloud properties during the year?*
- *Can Large Eddy Simulation modeling adequately capture the observed temporal and spatial variability of surface fluxes, boundary layer mixing, aerosol and CCN properties, cloud-aerosol interactions, and cloud properties over the SGP site?*
- *How can the high-resolution aircraft data coupled with Large Eddy Simulation modeling and routine ARM measurements be used to develop new parameterizations of sub-grid scale variability associated with boundary layer turbulence and shallow clouds?*

Post-campaign research will employ a combined data analysis and modeling approach to address these science questions. The data analyses will leverage and integrate measurements from both the routine SGP 'megasite' sampling and intensive sampling on G-1 aircraft flight days. Modeling studies are planned over a range of spatial scales, from cloud-resolving (Δx = 10 – 100 m), to cloud-scale resolving (Δx = a few km), to regional and synoptic spatial scales (Δx > 10 km). Our research has been divided into seven broad categories described in the Sections 4.2-.8. They are not independent efforts. Instead, they are collaborative efforts conducted over several years to integrate knowledge gained among the areas so that we can achieve our primary objective of obtaining a more holistic understanding of the life cycle of shallow clouds by coupling cloud macrophysical and microphysical properties to land surface properties, ecosystems, and aerosols**.**

4.2 Analyses Coupling Diverse Measurements and Ensuring Data Consistency

Several analyses need to be performed shortly after the campaign to ensure consistency obtained from the diverse types of measurements collected by the aircraft and at the surface. In addition, these analyses will be useful, and in some cases critical, for any investigator using the HI-SCALE data from the ARM archive.

Implementing Consistent Time Stamps and Cloud Flags. While many of the “standard” measurements on the G-1 aircraft will be provided on a common time stamp (at 1 and 10-s intervals), data from research grade instruments (e.g., HR-ToF-AMS, CIMS, miniSPLAT) will need to be averaged or interpolated to provide data at the same timestamps as other data. This will permit comparisons of various meteorological, cloud, trace gas, and aerosol measurements and ensure that trends are consistent. This will be particularly important as the aircraft flies through convective eddies and across cloud boundaries when rapid changes are expected in short time intervals. Two types of cloud flags will be applied: one to indicate when the G-1 aircraft is within a cloud and another when the CVI inlet is used to differentiate between sampling interstitial aerosols within a cloud and sampling cloud droplets.

Comparing In situ Aircraft and Surface Instrumentation. The flight paths will take the G-1 over the Central Facility several times for each flight. It is important to compare the differences in the aircraft in situ data with the in situ and remote sensing data from ground instruments. For example, meteorological quantities sampled by the aircraft will be compared with radiosonde and other remote sensing data (e.g., Atmospheric Emitted Radiance Interferometer [AERI], Raman, and Doppler lidar). When the aircraft is within the convective boundary layer, we expect that some trace gas and aerosol quantities will be well mixed so that the measurements at the surface and aloft will be quite similar (e.g, Zaveri et al. 2012). For fast-reacting gases and semi-volatile aerosol species, however, there may be substantial differences. The most interesting science will likely come from periods in which the surface and aircraft measurements aloft are not the same. The G-1 measurements of cloud properties also need to be compared with various routine remote-sensing cloud radar and lidar measurements. We will first need to determine when the G-1 flew through radar (Figure 6) and lidar scans, then identify which radar or lidar measurements can be directly compared to the aircraft cloud microphysical or aerosol property data, and finally compare the measurements to determine whether they are consistent. We expect shallow cumulus clouds with low liquid droplet concentrations will be challenging to detect by the SACR. The G-1 in situ cloud microphysics measurements (e.g., cloud drop-size distribution) will be used to compute radar reflectivity to quantify the sensitivity of the scanning cloud radar in detecting a variety of shallow cumulus clouds over its scan range at the SGP. This will provide useful guidance in the interpretation of the scanning cloud radar data for the data analyses and future operations.

Coupling Convective Eddies and Clouds Along Multiple-altitude Transects. The ambient winds will transport convective eddies and clouds downwind; therefore, the stacked aircraft transects will not sample instantaneous eddies coupled with either the surface or cloud properties. Instead, the data will be shifted in time, on the order of tens of minutes. Therefore, a separate data set will be created that uses the ambient winds to shift the time series on each transect to properly couple boundary layer measurements at multiple altitudes. In addition, we will construct probability density functions (PDFs) using the aircraft data to characterize many cloud and boundary layer properties in a way that is useful for developing and evaluating convective parameterizations.

Performing CCN Closure Studies. Closure studies for CCN are very useful to identify any measurement artifacts from a collection of instruments that are not apparent from examining the measurements separately. We will use aerosol size and composition (assuming internal mixing) with Kohler theory to calculate CCN at several saturations and compare those values with observed CCN, similar to Mei et al. (2013). This analysis will be segregated by aircraft altitude (e.g., below-cloud and in-cloud). Measurement uncertainties will be included in both analyses. We do not expect a perfect agreement in the closure studies, but the observed and calculated quantities should be highly correlated. For periods in which the calculated and observed CCN do not agree, that may be an indication that the aerosol mixing state is not internally mixed. For those periods, we will examine the SPLAT measurements to determine whether mixing state significantly affects observed CCN.

Deriving Secondary Products from Research-grade Instruments. By default, the HR-ToF-AMS measures non-refractory, sub-micron aerosol mass. Additional processing of the HR-ToF-AMS mass spectra data will be performed to obtain the size distribution of aerosol composition, while Positive Matrix Factorization (PMF) techniques will be used to derive components of organic aerosols. These secondary products are needed to determine what sources contribute to aerosols over the SGP site and whether the relative contribution of fresh (less oxygenated compounds) and aged (more oxygenated compounds) aerosol affect CCN concentrations.

4.3 Variability Resulting from Land Ecosystem and Their Effects on Clouds

Data collected during HI-SCALE will be used to address a range of questions related to land-atmosphere-cloud interactions, including the importance of horizontal heterogeneity in both thermodynamics and dynamics, the impact of clouds on the surface radiation budget, and the variability in biogenic emissions on aerosol distributions.

Heterogeneity in the land use, land cover (e.g., vegetation), and soil moisture can have an important impact on boundary layer turbulence. Likewise, shallow cumulus clouds, with their bases a kilometer or more above the surface, have a flux footprint that is quite large – meaning that they “feel” a relatively large area of the surface that can span a range of land use/cover type and soil moisture. Wavelet decomposition will be used to obtain turbulent fluxes of heat and moisture from the aircraft data and will be used to determine the important spatial scales that manifest in the turbulent boundary layer (e.g., Karl et al. 2013). We will attempt to link the spatial scales to the underlying surface as well as to well established boundary layer scales, such as the boundary layer depth and the Deardorff convective velocity scale (w^*). Earlier work has developed a parameterization of the PDFs of temperature and humidity (Berg and Stull 2004), but this approach neglected variability in the surface characteristics. The analysis will also be expanded to examine three-dimensional PDFs of temperature, humidity, and vertical velocity, and methods that can be used to parameterize the distributions will be explored. These distributions will also be compared with those generated by LES described in Section 4.7.

The surface fluxes of water, energy, and carbon are determined by the amount of sunlight (both direct and diffuse) that reaches the surface, the amount of shallow or deep soil moisture that is available for evapotranspiration, and the heat flux into the soil. The presence of broken clouds introduces additional heterogeneity because of reductions in the direct solar radiation associated with cloud shadows and an increase in the diffuse radiation—even above that seen in clear-sky conditions (Berg et al. 2011a), and feeds back through changes in the surface fluxes. Spatial heterogeneity in the surface albedo also has an important impact on the surface radiation budget, and surface-based measurements of albedo are problematic because of the small field of view. Data from HI-SCALE coupled with the SGP surface site measurements will be used to examine the impact of clouds on the surface radiation budget and to document the surface albedo over a larger area and with greater detail than is possible with the surface measurements alone. The airborne data can also be used to evaluate ARM data products designed to represent the spatial distribution of the downwelling shortwave radiation.

Biogenic emission rates are a function of plant type, solar radiation, and soil moisture available for transpiration. Large gradients in biogenic emissions are expected in the vicinity of the SGP site (Figure 9) due to variations in plant types and factors that affect stress in plants. The differences in biogenic emissions are anticipated to result in variability in the amount of new particle formation and SOA in the region. Using techniques similar to those applied for turbulence statistics of temperature, humidity, and winds, VOC data from the aircraft will be analyzed to determine spatial variability in SOA precursors and their emissions (Figure 9). We will investigate the relative role of heterogeneity in biogenic emissions, transport, and/or boundary layer turbulent mixing contributed to observed SOA that will help us understand the role of local and distant aerosol sources on CCN at cloud base.

4.4 Effect of Entrainment on CCN Concentrations

Entrainment, across both the top of the convective boundary layer and through the edges of clouds, remains an outstanding issue in the community that is critical for understanding trace gas (including water vapor) and aerosol concentrations within the boundary layer as well as the life cycle of convective clouds. Entrainment at the boundary layer top generally leads to a dilution of trace gas and aerosol concentrations as the day progresses, leading in turn to a relative reduction in the number of CCN. The life cycle of convective clouds is also significantly influenced by entrainment of ambient air that dilutes and dries the clouds. In deep convective clouds, entrainment provides the CCN responsible for secondary activation.

HI-SCALE data will be used to investigate entrainment, across both the top of the convective boundary layer and through the edges of clouds. Past research, including studies conducted by members of our team (e.g. Berg et al. 2011b; Yang et al. 2015), have used conserved passive tracers as markers of the source region of air. Passive tracer data can be combined to form so-called “mixing diagrams” (Paluch 1979). These special diagrams can be used to determine the source regions of air, providing an estimate of the amount of mixing that has occurred between two source volumes. By selecting one volume inside and one outside of clouds, the amount of entrainment through the cloud edges can be estimated. Likewise, if one volume is selected to be within the boundary layer and one is selected to be above the boundary layer, the amount of entrainment across the boundary layer top can be inferred. The vast majority of past studies have used moist static energy and total water vapor mixing ratio (e.g., Reuter 1986). One disadvantage of this approach is the inherent correlation between these two variables (as moist static energy is a function of the mixing ratio), but that can be avoided in the analysis of HI-SCALE data because of the availability of trace gas measurements such as those from the CIMS and CO instruments. The trace gas data will be combined with the measured moisture and temperature to construct mixing diagrams for specific flights and estimates of entrainment will be generated. These estimates can be compared to other estimates of entrainment made using the suite of remote sensing instruments at the Central Facility (e.g., Wagner et al 2013) and other methods derived from aircraft data (e.g., Lu et al. 2012c).

4.5 Effect of Particle Growth and Mixing Rate on CCN

Several studies have shown that new particle formation events and the subsequent growth of particle populations can influence CCN concentrations. Models, however, poorly represent these events and the evolution of aerosol size distribution and thus simulated CCN contains large uncertainties. Based on the data collected from the 2013 NPFS, the formation of new particles at the SGP site occurs frequently during the spring and less frequently during the summer. Vertical profiles of 10-20 nm-diameter particles for one day are shown in Figure 12. During the morning, most of these particles are located above the surface, with highest concentrations at 500 m atmospheric surface layer (ASL). ; therefore, nucleation likely occurred above ground so that emissions may have little impact on the chemical processes that control particle nucleation and the early stages of particle growth. Nanoparticle concentrations were relatively constant for the rest of the afternoon within the well mixed boundary layer. These observations emphasize the importance of vertical profile measurements of the particle size distributions.

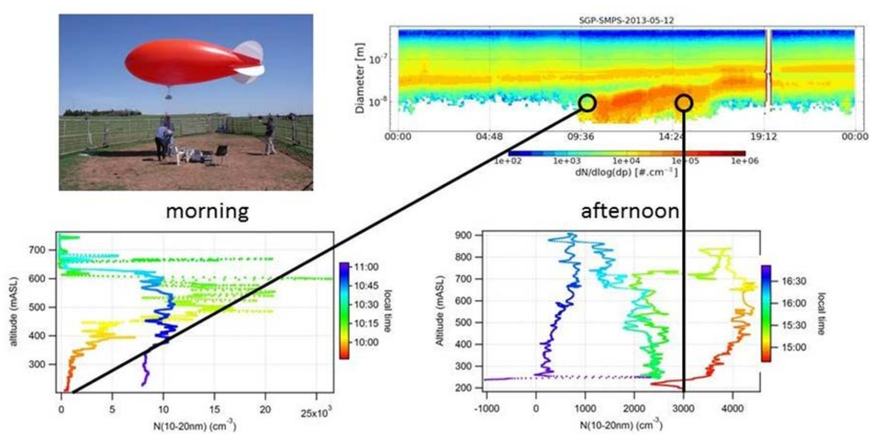

Figure 12. Tethered balloon data showing vertically resolved data on 10-20 nm diameter-particle number concentrations during the 2013 NPFS at the SGP site.

Measurements of nanoparticle size and composition and gas-phase precursors obtained during HI-SCALE promise to produce a wealth of information on the contribution of biogenic and anthropogenic emissions to the formation and growth of aerosols. We will perform nucleation and growth-rate analyses (e.g., diffusion and volume reaction controlled) to determine how the observed nanoparticle growth rates compare to the current model assumptions based on findings from McMurry and Wilson (1982, 1983), Wilson and McMurry (1981), McMurry et al. (1981), and Friedlander (2000). Since we will rely on aircraft data, the relationships will be more complex than the surface-based analysis shown in Figure 12, depending on the horizontal variability in new particle formation events. We will also connect the growth of particles for new particle formation events both in the boundary layer and in the free troposphere to CCN that are entrained into clouds to determine the importance of these events on cloud properties.

We will also investigate how effective condensation-based methods are for treating the growth of particles in aerosol microphysics models are in capturing the composition and growth of the newly formed particles observed during HI-SCALE. Predicted model size distributions for these events using sulfuric acid and organic formation rates can be derived from the HR-ToF-AMS and the CIMS, using a method described by Pierce et al. (2011). In this approach, the net condensation rate to a particle of known size with a particle-phase and gas-phase composition is provided using the Volatility Basis Set (VBS) framework (Donahue et al. 2011). This net condensation rate results in a non-reactive, size-dependent growth rate, which we can compare to observed growth rates in order to determine the relative role of non-reactive (reversible) condensation on growth.

Particle formation and growth is closely coupled with SOA formation and mixing state, i.e., the distribution of chemical components within a population of particles. A perfect internal mixture has equal amounts of all chemical species in all particles, whereas an external mixture has one chemical species per particle. The mixing state in real atmosphere varies between these two extremes. It is also known that CCN concentrations depend on the aerosol mixing state, but there have been few observational and modeling studies using single-article measurements to demonstrate and quantify that dependence. For example, Matsui et al. (2104) showed that the internal mixing assumption commonly used by climate models resulted in an average error of 18% for CCN concentrations in their case, but other studies suggest that this error could be higher. EMSL measurements will provide the measurements of aerosol mixing state for the first time at the ARM SGP site. We plan to use the measurements to better understand how climate-relevant properties of aerosols (e.g., size, composition, volatility) evolve and affect CCN concentrations as a function of aging and mixing of various aerosol sources.

Single-particle measurements from miniSPLAT and SPLAT will characterize the detailed chemical composition and morphology of particles. An example of particle classes derived from miniSPLAT measurements collected by the G-1 aircraft during the TCAP campaign (Berg et al. 2015b) is given in Figure 13. For this flight, particles were dominated by organic matter and sulfate; however, the mixture of these two quantities is not constant with some particles having the total mass comprised of 30% or more of sulfate while other particles have 10% or less. This variation in relative amount of sulfate that is more hydrophilic than organic matter could affect the overall CCN activation properties of the particle population. By analyzing a large number of particles, we will first quantify the aerosol mixing state using a new entropy and diversity metric method (Riemer and West 2013). The quantitative mixing states will then be compared and correlated with collocated data on hygroscopic properties and CCN concentrations to gain a more complete understanding of the aerosol effect on CCN at the SGP site. These results will be segregated into periods dominated by anthropogenic, biogenic, and biomass burning aerosol sources to determine whether the differences in the aerosol sources have any impact on cloud properties over the SGP site.

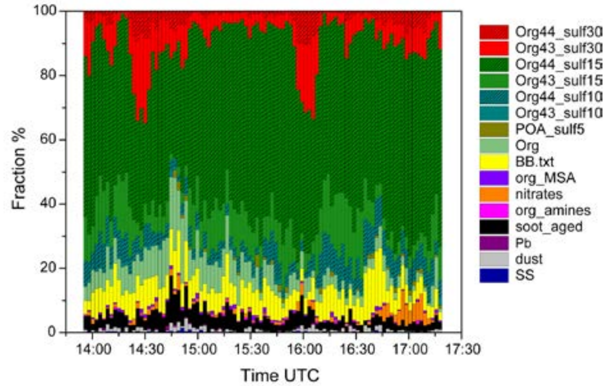

Figure 13. Particle classes derived obtained from miniSPLAT deployed on the G-1 aircraft during the TCAP campaign.

We will also uses the single-article measurements in conjunction with the bulk aerosol and trace gas measurements to investigate current model representations of the evolution and lifetime of SOA particles (semi-volatile liquid-like vs. non-volatile semi-solid) and the role of low-volatility organics in particle nucleation and growth to CCN sizes. Phase and volatility of SOA is an important emerging area of research as illustrated in Figure 14 and SPLAT II measurements have provided groundbreaking insights (Vaden et al. 2011) that have been implemented into regional (Shrivastava et al. 2013b) and global (Shrivastava et al. 2015) models. The relative role of anthropogenic, biogenic, and biomass burning sources on SOA in the vicinity of the SGP site will be investigated using the analyses described in Section 4.1. We are particularly interested in examining the importance of isoprene epoxydiols formed under low-NO_x conditions on enhanced isoprene-related SOA yields under acidic conditions (Surrat et al. 2008, 2010). Since there are relatively large errors in climate model predictions of SOA that could affect simulated CCN, analyses will be performed to determine whether there is a strong relationship between the observed variations in total SOA concentrations and SOA components with CCN concentrations.

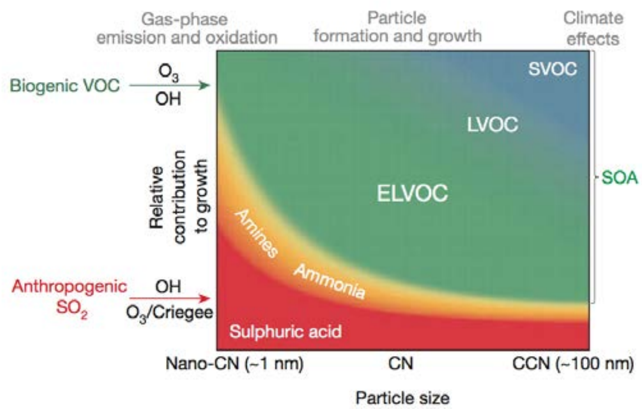

Figure 14. The relationship between precursor trace gases and aerosol growth to CCN sizes (from Ehn et al 2014).

While a large number of aqueous-phase reactions are proposed that produce organics within clouds, there is little in situ experimental data to verify the importance of these reactions in ambient environments. We plan to couple HR-ToF-AMS and miniSPLAT analyses with data from cloud probes and other trace gas instruments (e.g., CIMS) to provide an estimate of organic aerosol production from cloud-processing in the ambient environment. As shallow clouds evaporate, the additional organic aerosol mass could alter CCN concentrations as they are entrained into other clouds that form.

4.6 Coupling Aerosols to Cloud Properties

HI-SCALE data can be used to investigate how different aerosol loading and land-surface conditions impact boundary layer properties and CCN, which in turn can impact convection and precipitation. This is especially the case for the transition from shallow to deep convection over the SGP site. Earlier work in the vicinity of Oklahoma City during CHAPS showed that aerosol can have a measurable impact on the cloud microphysical and optical properties (Berg et al. 2011b). In that study, CO was used as a tracer of opportunity to mark individual clouds that are impacted by anthropogenic aerosol. Our analyses on cloud-aerosol interactions will be similar in some respects to those performed for CHAPS; however, we anticipate sampling a larger range of aerosol environments during HI-SCALE that will provide information needed to inform climate models. We will also conduct a systematic study of boundary layer properties (depth, stability, inversion strength, and turbulence), shallow convection clouds, the transition from shallow to deep convection, and precipitation for cases with a wide range of aerosol properties using the ARM long-term measurements to understand the role of aerosols in the vicinity of the SGP site. A unique aspect of this work is being able to not only evaluate interstitial aerosols, but also evaluate cloud-borne aerosols via the CVI inlet sampling to be performed using HR-ToF-AMS, and miniSPLAT. Rarely are model simulations of cloud-borne aerosols evaluated.

During conditions with non-absorbing and hydrophilic aerosols, there are increased droplet number concentrations (assuming a constant updraft velocity within the cloud), delaying the onset of precipitation and suppressing drizzle (Rosenfeld 1999), which could impact the transition of shallow to deep convection. In contrast, during periods with absorbing and hydrophobic aerosols, surface temperature will be reduced, but the top of the boundary layer will warm, stabilizing the boundary layer and suppressing convection (e.g., Feingold et al. 2005; Fan et al. 2008, 2015). For shallow convective clouds, cloud-aerosol interactions could enhance entrainment (Albrecht 1989; Ackerman et al. 2004) and consequently impact the cloud lifetime, which could also play a significant role in the transition of shallow to deep clouds. For the SGP site, we anticipate that absorbing conditions will occur only when biomass burning is large.

Therefore, we plan to first group HI-SCALE sampling periods by aerosol type (e.g., dominated by anthropogenic, biomass burning, or biogenic sources) and loading (small vs. large) to examine various cloud property statistics from the G-1 measurements under different aerosol regimes. For each group, surface fluxes, boundary layer characteristics, CCN concentrations, and cloud macrophysical, dynamical, and microphysical properties will be analyzed from the G-1 measurements as well as the ARM network of surface-based measurements. Application of the surface-based measurements is critical to sample as large a population of clouds as possible over a wide range of conditions. Within each group, the analyses will be separated into different surface vegetation and soil moisture conditions to investigate how land surface and boundary layer properties affect turbulent mixing of aerosols and their entrainment into clouds.

Regional-scale and high-resolution model simulations will be performed and combined with observational analysis to gain a better understanding and to separate causality from correlation analyses. LES and cloud-scale resolving simulations, to be described in Sections 4.7 and 4.8, will be performed under the different aerosol regimes. The simulations will be examined to explain similarities and discrepancies with observed relationships on how aerosols affect cloud properties as well as how clouds affect aerosol properties. Different treatments for droplet activation will be examined. The Abdul-Razzak-Ghan scheme (Abdul-Razzak et al. 1998; Abdul-Razzak and Ghan 2000, 2002) is used by both the Community Atmosphere Model (CAM) and the WRF, but other schemes have been proposed (e.g., Fountoukis and Nenes 2005); therefore, it would be useful to compare different cloud droplet number concentrations given by both schemes when the same aerosol characteristics are used. A new parameterization for convection that accounts for aqueous chemistry in parameterized clouds has recently been developed for application in regional-scale models (Berg et al. 2015a). The new parameterization will be evaluated using data collected from HI-SCALE, standard ARM observations, and other observational networks. This analysis will include comparing simulations with in situ measurements of the chemical composition of the cloud-drop residuals collected with the CVI.

4.7 Integrating Observed Process-level Understanding Using LES Modeling

Large Eddy Simulation (LES) modeling will be used to synthesize numerous measurement types, obtain new process-level understanding, and form the basis of developing and testing new parameterizations suitable for spatial scales used by the next generation of climate models (i.e., ~10 km). We plan to use the WRF model (Skamarock et al. 2005; Grell et al. 2005; Fast et al. 2006) with grid spacings ranging from 10 to 100 m for this purpose. While there are many LES models, WRF is one of the few LES models that also include multiple parameterization choices for variable land-surface forcing, atmospheric chemistry controlling aerosol evolution, and the full range of cloud-aerosol interactions. Our team has been a leader in the atmospheric community in developing these treatments and making them available in the public version of WRF (e.g. Fast et al. 2006; Gustafson et al. 2007; Zaveri et al. 2008; Chapman et al. 2009; Barnard et al. 2010; Zhao et al. 2010; Yang et al. 2011; Shrivastava et al. 2011; Ma et al. 2014; Berg et al. 2015a).

As with most LES models (Figure 15), WRF has been used by the atmospheric community and our team (Xiao et al. 2014, 2015) to study boundary layer turbulence and cloud processes. Applying WRF at LES scales for HI-SCALE will be among the first applications with such detailed complexity of atmospheric processes that also need a commensurate amount of surface and airborne observations to better understand the connections and feedbacks associated with the shallow clouds, turbulent mixing, the aerosol life cycle, and land ecosystems. This will include evaluating how well the Community Land Model (CLM) at high-spatial resolution represents variations in heat, moisture, and momentum fluxes and biogenic emission rates over the SGP site associated with variations in land use, vegetation types, and soil moisture. We will also test simple and complex treatments of aerosols in the LES model. Simple aerosol treatment will be the default aerosol model included in CAM5, called Modal Aerosol Module (MAM; Liu et al. 2012) and a detailed sectional aerosol model, Model for Simulating Aerosol Interactions and Chemistry (MOSAIC; Zaveri et al. 2008), developed under ASR support and recently extended to include new representations of SOA (Shrivastava et al. 2011, 2013b; Zaveri et al. 2014) as well as explicit treatments of new particle formation (Lupascu et al. 2015). These aerosol treatments have been coupled to cloud via various cloud-aerosol interaction processes (e.g., activation, aqueous chemistry, wet scavenging) already included in WRF.

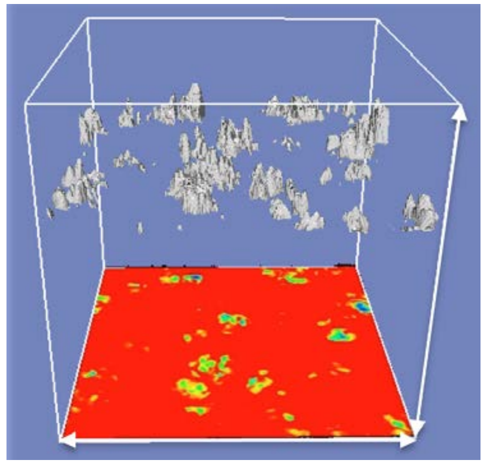

Figure 15. Example LES model representation of shallow convective clouds and their impact on downwelling shortwave radiation (color) over the SGP site.

Since ARM is initiating a routine high-resolution modeling component this year (ARM Climate Research Facility, 2014a), we plan to work closely with that team to learn the best way to configure WRF for HI-SCALE. This work would include choosing appropriate forcing data sets developed from SGP measurements. We anticipate that ARM's effort will focus on simulating cloud dynamics and microphysics in the LES modeling framework. In contrast, we will have more resources and flexibility to explore a wider range of processes that significantly increases the complexity and computational cost associated with detailed vegetation dynamics, the aerosol life cycle, and cloud-atmosphere interactions. Our modeling research will also make recommendations on what level of detail is needed for future routine LES modeling at the SGP site.

WRF also has the ability to include domain nesting. While we plan to run WRF as a traditional LES model that has a single domain using routine SGP measurements and HI-SCALE data as boundary conditions, we also anticipate running WRF that nests the LES domain within a regional-scale modeling domain that can represent the evolution of meteorology, clouds, and aerosols as those conditions are transported over the SGP site. In this way, we can compare statistics (e.g., PDFs) and averages of cloud properties over the LES domain with cloud predictions over larger grid cells to determine if the parameterizations of various processes on the larger-scale outer domain can adequately represent sub-grid-scale variability that is evident in both the HI-SCALE observations and the LES results.

4.8 Improving Parameterizations of Clouds, Aerosols, and Their Interactions

The LES modeling studies of HI-SCALE described in the previous section will be used in conjunction with the HI-SCALE measurements to provide a benchmark to test and evaluate parameterizations that can be used by regional and global models.

One of ASR's ongoing parameterization efforts is associated with Cloud Layers Unified by Binormals (CLUBB; Larson et al. 2005; Larson et al. 2005). While CLUBB was originally designed to seamlessly parameterize both boundary layer processes and shallow clouds (as opposed to two separate parameterizations), we have been working to enhance its capabilities so that it can also represent deep convection (Wong et al. 2015). CLUBB is also a candidate parameterization for the Accelerated Climate Modelling for Energy (ACME) model. We plan to test CLUBB in two modeling frameworks: the single-column version of CAM and 3-D simulations in WRF. In the single-column version, cloud statistics generated from HI-SCALE aircraft data will be used to evaluate how well CLUBB represents shallow clouds as a function of meteorological regime. In WRF, CLUBB will be tested at both cloud-system-resolving scales (grid spacing of a few kilometers) and with a grid spacing typically used by climate models (10 km and greater). In this way, we can evaluate the scale dependency of CLUBB in relation to the observed cloud properties around the SGP site. While HI-SCALE aircraft measurements will focus on shallow clouds, there will be instances when the aircraft will capture the transition from shallow to deep convection. We expect that there will be many instances of deep convection over the SGP site that will be sampled by other routine 'megasite' measurements on non-flight days. Therefore, we will evaluate CLUBB for both shallow and deep convective clouds during the HI-SCALE sampling periods. Cloud-aerosol interactions will eventually be included by CLUBB, and the variability of aerosol properties and cloud-aerosol interactions sampled by the aircraft will provide critical data needed to test that aspect of CLUBB.

We also plan to perform WRF simulations at cloud-system-resolving scale and grid spacings typically used by climate models to examine issues associated with organization of convection and to test and evaluate other parameterizations of land-surface processes, boundary layer turbulence, microphysics, and the aerosol life cycle. For example, we will test new methods of representing SOA and assess their impacts on cloud-radiation-precipitation interactions over the SGP region. The HI-SCALE data set will be extremely valuable for testing and constraining recent SOA treatments within WRF-Chem that have applied some of the latest insights related to SOA volatility and functionalization/fragmentation reaction pathways governing the formation and evolution of SOA in the atmosphere (Shrivastava et al. 2013b), including the interactions between aerosol chemistry and clouds in the vicinity of Oklahoma City, Oklahoma (Shrivastava et al. 2013a). This new scheme may be a candidate treatment for the next generation of CAM or ACME and preliminary work has already been conducted to evaluate its performance within the CAM5 model as described by Shrivastava et al. (2015). Likewise the HI-SCALE data and routine ARM observations will also be used to test new parameterizations of cloud-aerosol interactions for sub-grid convective clouds (Berg et al. 2015a). Therefore, the HI-SCALE measurements will be a useful data set for future climate model evaluation.

5.0 Conclusion

The proposed deployment fits into ARM's new 10-year vision (ARM Climate Research Facility 2014b) by leveraging the 'megasite' measurement strategy at the SGP site and high-resolution modeling to address outstanding science questions related to the life cycle of shallow clouds. As discussed previously, shallow clouds and the transition to deep convection and precipitation are poorly represented in climate models and remain a major source of uncertainty in climate simulations. The proposed instrument deployment and sampling strategy will obtain the measurements needed to quantify the influence of inhomogeneity in land use, vegetation, soil moisture, convective eddies, and aerosol properties on the evolution of shallow clouds as well as the feedbacks of cloud radiative effects on heat, moisture, and momentum fluxes and on aerosol photochemical processes. This information is critical to achieve a more holistic understanding of the life cycle of shallow clouds and develop improved parameterizations that can help reduce the uncertainties in climate and earth system models. This research on the cloud life cycle, aerosol life cycle, and cloud-aerosol-precipitation interactions is consistent with the mission of the ASR Program (ASR 2010) and includes land-atmosphere-cloud interactions that are now being investigated in more detail by ASR scientists.

The proposed research also addresses three of the five primary goals of DOE's Climate and Environmental Sciences Division (CESD 2012), including 1) synthesize new process knowledge and innovative computational methods advancing next-generation, integrated models of the human-earth system, 2) develop, test, and simulate process-level understanding of atmospheric systems and terrestrial ecosystems, extending from bedrock to the top of the vegetative canopy, and 3) enhance the unique capabilities and impacts of the ARM and EMSL scientific user facilities and other DOE Biological and Environmental Research community resources to advance the frontiers of climate and environmental science.

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