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Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems (HI-SCALE) Field Campaign Report

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Acronyms and Abbreviations

AAF	ARM Aerial Facility
AMS	aerosol mass spectrometer
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Radiation
BNL	Brookhaven National Laboratory
CCN	cloud condensation nuclei
DOE	U.S. Department of Energy
EMSL	Environmental Molecular Sciences Laboratory
G-1	Gulfstream 1 aircraft
h	hour
HI-SCALE	Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems
IOP	intensive operation period
km	kilometer
m	meter
mm	millimeter
NDVI	Normalized Difference Vegetation Index
nm	nanometer
PCASP	passive cavity aerosol spectrometer probe
PNNL	Pacific Northwest National Laboratory
PTR-MS	proton transfer reaction-mass spectrometer
SGP	Southern Great Plains
SMPS	scanning mobility particle sizer
SPLAT II	single-particle laser ablation time-of-flight mass spectrometer

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1.0 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 land surface, boundary layer, and aerosol properties. The Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems (HI-SCALE) campaign was designed to provide a detailed set of measurements that are needed to obtain a more complete understanding of the lifecycle of shallow clouds by coupling cloud macrophysical and microphysical properties to land surface properties, ecosystems, and aerosols. Some of the land-atmosphere-cloud interactions that can be studied using HI-SCALE data are shown in Figure 1.

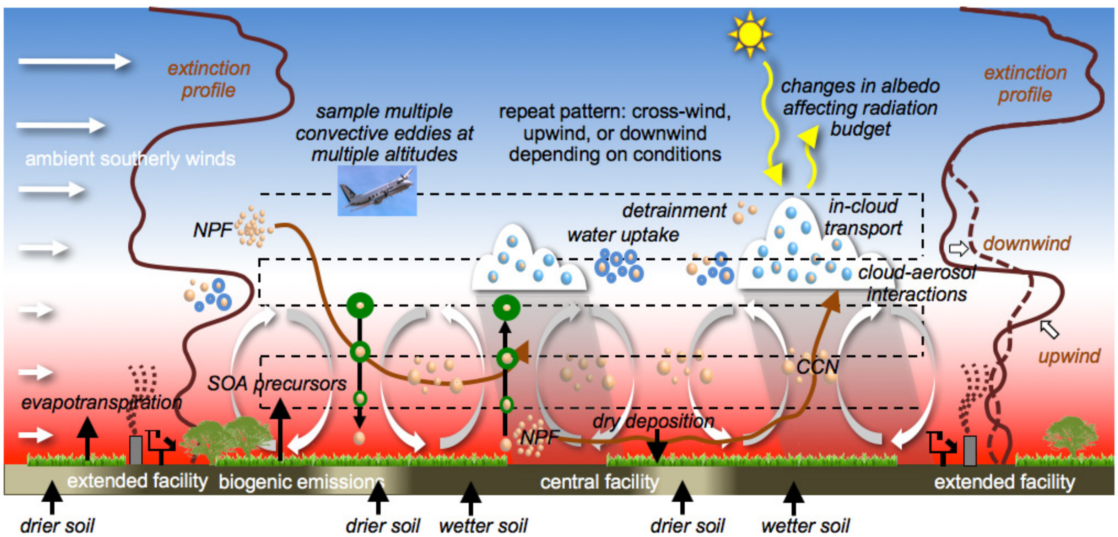

Figure 1. Schematic diagram depicting land-atmosphere, boundary-layer, and aerosol processes that influence the lifecycle of shallow convective clouds.

HI-SCALE consisted of two 4-week intensive operation periods (IOPs), one in the spring (April 24-May 21) and the other in the late summer (August 28-September 24) of 2016, to take advantage of different stages of the plant lifecycle, the distribution of "greenness" for various types of vegetation in the vicinity of the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility Southern Great Plains (SGP) site, and aerosol properties that vary during the growing season. As expected, satellite measurements indicated that the Normalized Difference Vegetation Index (NDVI) was much "greener" in the vicinity of the SGP site during the spring IOP than the late summer IOP as a result of winter wheat maturing in the spring and being harvested in the early summer. As shown in Figure 2, temperatures were cooler than average and soil moisture was high during the spring IOP, while temperatures were warmer than average and soil moisture was low during the late summer IOP. These factors likely influence the occurrence and lifecycle of shallow clouds.

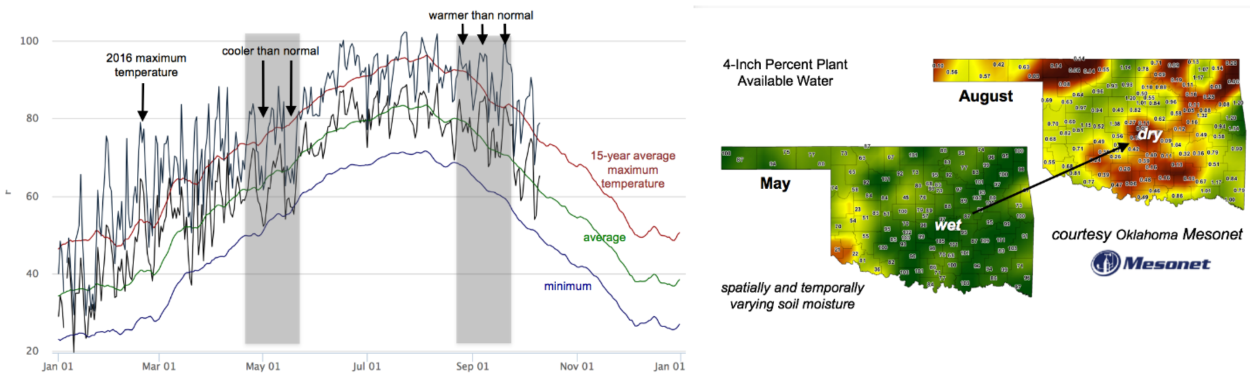

Figure 2. Temperatures observed during 2016 compared to climatology (left) and soil moisture distribution during May and August of 2016.

Most of the instrumentation was 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 (CCN) concentrations. The specific instrumentation is listed in Table 1. The team of scientists participating in the G-1 flights were from Pacific Northwest National Laboratory (PNNL), Brookhaven National Laboratory (BNL), and the University of Washington. Routine ARM aerosol measurements made at the surface were supplemented with aerosol microphysical properties measurements, with support from the DOE Environmental Molecular Sciences Laboratory (EMSL) User Facility and the Atmospheric System Radiation (ASR) program. This included deploying a scanning mobility particle sizer (SMPS) to measure aerosol size distribution, a proton transfer reaction-mass spectrometer (PTR-MS) to measure volatile organic compounds, an aerosol mass spectrometer (AMS) to measure bulk aerosol composition, and the single-particle laser ablation time-of-flight mass spectrometer (SPLAT II) to measure single-particle aerosol composition at the SGP site Guest Instrumentation Facility. In this way, characterization of aerosol properties at the surface and on the G-1 were consistent. In addition, the HI-SCALE: Nanoparticle Composition and Precursors add-on campaign was conducted during the second IOP in which several state-of-the-science chemical ionization mass spectrometers were deployed to measure nanoparticle composition and precursors. Scientists participating in the surface measurements were from PNNL, BNL, University California–Irvine, Augsberg College, Colorado University, Aerodyne Inc., and Aerosol Dynamics Inc.

Table 1. Instrumentation deployed on the G-1 aircraft during HI-SCALE.

Measurement	Data Source Name
Meteorology	• Aircraft-integrated meteorological measurement system • Meteorology/State/Position Parameters
Cloud	• Fast cloud droplet probe (FCDP, 1-50 mm) • 2DS cloud particle imaging probe (2DS,10 mm-3 mm) • High-volume precipitation spectrometer imaging probe (HVPS, 150 mm–10 cm) • Cloud droplet probe (CDP, 1-50 mm) • Cloud imaging probe (CIP,10 mm- 3 mm) • Cloud spectrometer and impactor (CSI) • Cloud and aerosol spectrometer (CAS) • Water content monitor

Radiation	• Radiometer suite
Aerosol	• Condensation particle counter (CPC, > 10 nm) • Cloud condensation nuclei counter (CCN) • Ultra-high-sensitivity aerosol spectrometer (UHSAS) • Passive cavity aerosol spectrometer (PCASP) • Fast integrated mobility spectrometer (FIMS) • Aerosol mass spectrometer (AMS) • Mini-single-particle mass spectrometer (mini-SPLAT) • Optical particle counters after isokinetic and counter-flow virtual impact inlet
Trace Gases	• NO/Nox analyzer • Trace gas suite: CO, SO_2, ozone • Time-of-flight chemical ionization mass spectrometer (ToF CIMS)
Other	• Video • Worldview -3 satellite images of SGP/ARM

The G-1 aircraft completed transects over the SGP Central Facility at multiple altitudes below, within, and above clouds (Figure 1). During the first IOP, 17 G-1 flights were conducted with a total of 57.8 flight hours (3.4 h average duration). Nine of these flights sampled a significant number of clouds, with 6.5 total hours within clouds. The flight paths during the two IOPs are shown in Figure 3. The G-1 was based at the Bartlesville Municipal Airport, located ~150 km east of the SGP site. Most of the sampling was in the vicinity and upwind (south) of the SGP site. 21 G-1 flights were conducted for the second IOP with a total of 47.8 flight hours. On five days, two flights per day were conducted. Nine flights sampled shallow clouds with 1.1 total hours within clouds. The higher-than-normal temperatures reduced flight durations and caused earlier take-off times.

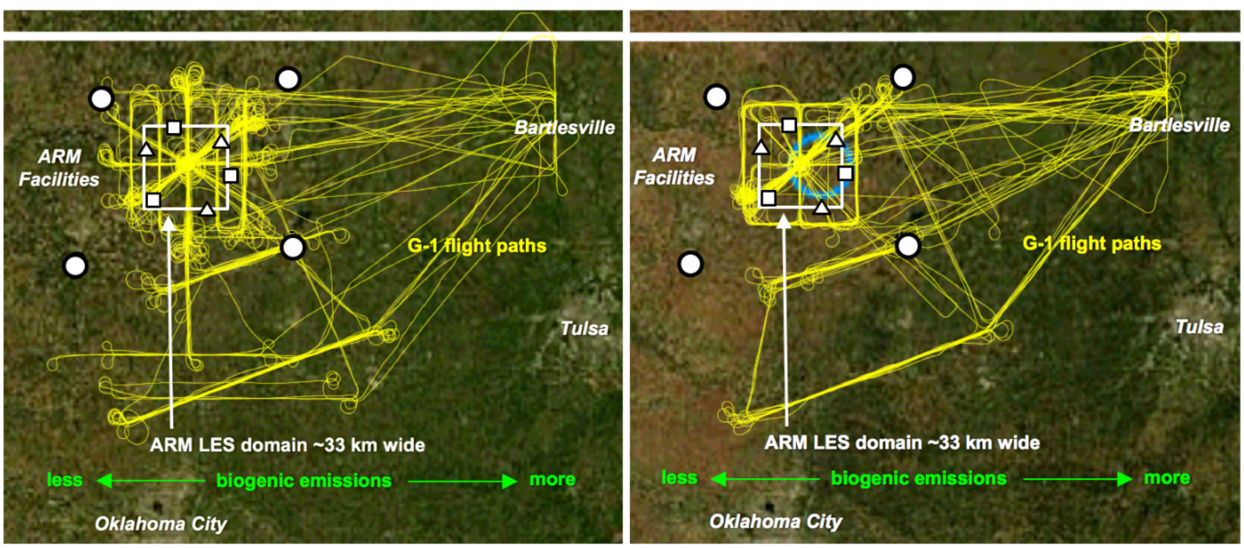

Figure 3. Flight paths during the first (left) and second (right) IOP of HI-SCALE.

While the objective of HI-SCALE was to study shallow convective clouds, deep convection was a notable event that occurred frequently during the first IOP and occasionally during the second IOP. The G-1 sampled conditions prior to deep convection, during deep convection in the vicinity of the G-1 flight paths, and after deep convection. For example, one G-1 flight during the first IOP had to be aborted due to lightning in the vicinity of the SGP site; the G-1 flight path and a couple of G-1 flights were delayed due to convection in the vicinity of the Bartlesville airport.

2.0 Results

Figure 4 shows the average cloud properties sampled during 11 of the G-1 flights from the first IOP. There is large variability in these cloud properties because the type and spatial extent of clouds sampled varied from day to day.

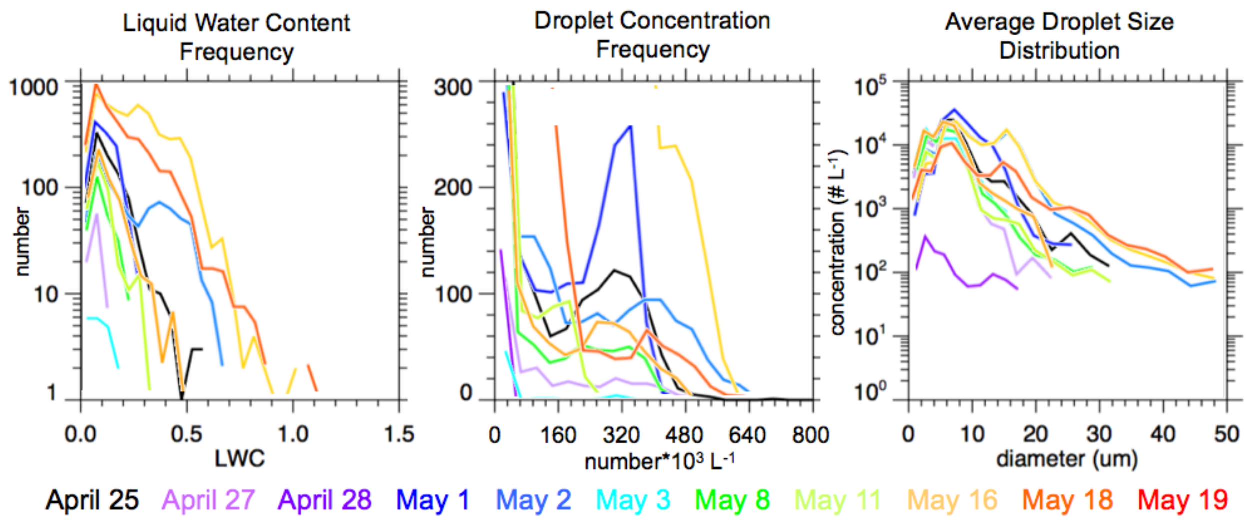

Figure 4. Average liquid water content frequency, drop concentration frequency, and droplet size distribution observed by the G-1 during the first IOP. Color denotes the flight day.

While data analysis is ongoing, it is instructive to examine preliminary results from a day with significant cloud population transitions. The conditions on August 30 during the second IOP were particularly interesting since the widespread shallow convection that formed in the late morning transitioned to a complex cloud population distribution during the afternoon as shown in Figure 5. Two G-1 flights were conducted on this day. As the G-1 took off for the first flight, convection started to form over southeastern Oklahoma, southern Missouri, and northwestern Arkansas, but clear skies remained over the SGP site. About half-way into the flight, shallow convection started to form over northern Oklahoma and southern Kansas as well. The G-1 deviated from its planned flight pattern to sample these shallow clouds soon after they formed. During the second flight, the relatively uniform field of shallow convection transitioned into a more complex cloud population. Some shallow convection transitioned to small precipitating cells that quickly dissipated while other shallow convection transitioned into isolated deep convection. Pockets of clear skies formed—some of them due to cold pools but others seemed to have formed for other reasons. The G-1 also indicated large gradients of aerosol populations in conjunction with the cloud distribution. The largest concentrations observed on that day near the SGP site are likely due to emissions from a power plant and refinery near Ponca City.

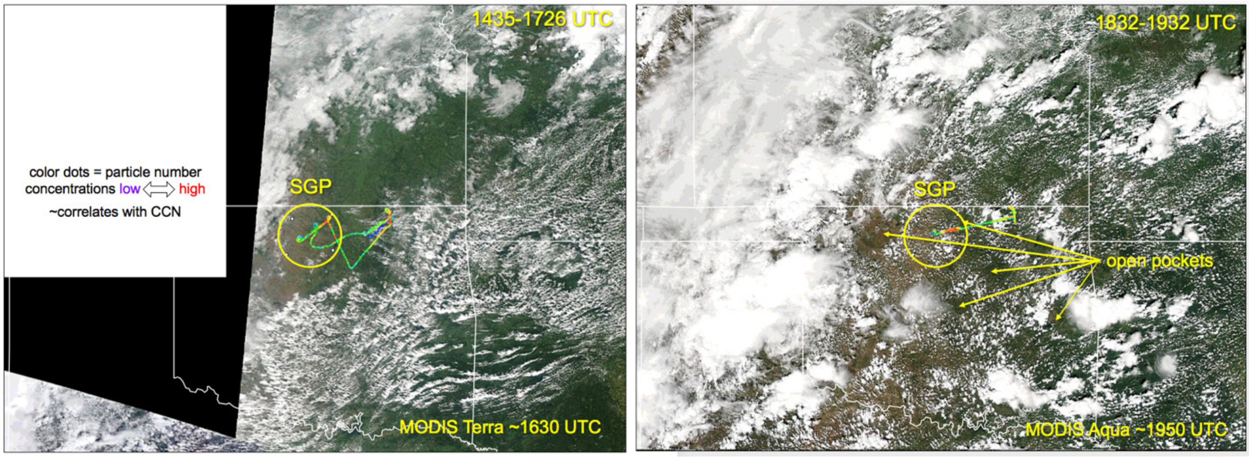

Figure 5. Cloud distribution in the vicinity of the SGP site during the morning (left) and afternoon (right) of August 30, 2016. Colored dots denote CPC aerosol concentrations measured along the G-1 flight paths.

We anticipate that the measurements from HI-SCALE will be used to address several important science questions including:

- 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 lifecycle 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 over the next several years 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’ instruments and intensive sampling on G-1 aircraft flight days. Modeling studies are planned over a range of spatial scales, from cloud-resolving Large-Eddy Simulation (LES, Δx = 10–100 m), 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 4.2-4.8 of the Science Plan (Fast et al., 2015). They are not independent efforts. Instead, they are collaborative efforts that will be conducted over several years to integrate our understanding so that we can achieve our primary objective of obtaining a more holistic understanding of the lifecycle of shallow clouds by coupling cloud macrophysical and microphysical properties to land surface properties, ecosystems, and aerosols**.**

3.0 Publications and References

Since the campaign finished approximately 6 months ago, no journal articles using HI-SCALE data have been published or submitted. The following are recent meetings and conferences where the HI-SCALE campaign was described and preliminary results were presented:

Fast, JD, LK Berg, CK Burleyson, J Fan, Z Feng, S Hagos, M Huang, A Guenther, P Gentine, C Kuang, M Ovchinnikov, J Shilling, M Shrivastava, J Smith, J Thornton, D Tuner, H.Xiao, J Wang, R Zaveri, and A Zelenyuk. 2015. Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems (HI-SCALE) Science Plan. DOE/SC-ARM-15-062. Available at: https://www.arm.gov/publications/programdocs/doe-sc-arm-15-062.pdf.

Fast, J, L Berg, B Schmid, L Alexander, D Bell, E D'Ambro, J Hubbe, J Liu, F Mei, M Pekour, T Pinterich, S Schobesberger, J Shilling, J Smith, S Springston, J Thornton, J Tomlinson, J Wang, and A. Zelenyuk. 2017. Preliminary findings from the recent Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems (HI-SCALE) field campaign: Invited Presentation. *ARM/ASR Principal Investigator Meeting*, Vienna, Virginia, March 13-16.

Fast, JD, LK Berg, B Schmid, L Alexander, E D'Ambro, D Bell1, E Brown, A Eiguren, D Hanson, J Hubbe, C Kuang, R Lindenmaier, J Liu, A Matthews, F Mei, M Pekour, T Pinterich, S Schobesberger, J Shilling, J Smith, S Springston, H Stark, K Suski1, J Thornton, J Tomlinson, J Wang, and A Zelenyuk. 2017. The Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems (HI-SCALE) campaign: Measurement strategy and preliminary findings. Poster. *ARM/ASR Principal Investigator Meeting*, Vienna, Virginia, March 13-16.

Fast, JD, LK Berg, B Schmid, L Alexander, D Bell, E D'Ambro, J Hubbe, J Liu, F Mei, M Pekour, T Pinterich, S Schobesberger, J Shilling, S Springston, JA Thornton, J Tomlinson, J Wang, and A Zelenyuk. 2017. The Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems Campaign: Measurement Strategy and Preliminary Findings. *Ninth Symposium on Aerosol-Cloud-Climate Interactions*. Seatlle, Washington, J3.6.

Fast, JD, LK Berg, B Schmid, ML Alexander, D Bell, E D'Ambro, JM Hubbe, J Liu, F Mei, MS Pekour, T Pinterich, S Schobesberger, J Shilling, SR Springston, JA Thornton, JM Tomlinson, J Wang, and A Zelenyuk. 2016. Improving the Understanding and Model Representation of Processes that Couple Shallow Clouds, Aerosols, and Land-Ecosystems. *2016 Fall AGU Meeting*, San Francisco, California, A43C-01.

Fast, JD, LK Berg, L Alexander, E D'Ambro, DM Bell, E Brown, A Eiguren, JM Hubbe, C. Kuang, R Lindenmaier, J Liu, AA Matthews, F Mei F, MS Pekour, T Pinterich, B Schmid, S Schobesberger, JE Shilling, JN Smith, S Springston, H Stark, KJ Suski, JA Thornton, J Wang, and A Zelenyuk-Imre. 2016. The Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems (HI-SCALE) campaign:

Measurement strategy and preliminary findings. *International Global Atmospheric Chemistry (IGAC) Project 2016 Science Conference*, Breckenridge, Colorado, September 26-30.

4.0 Lessons Learned

4.1 Flight Hours

One factor that went particularly well during HI-SCALE was that the number of flight hours was not predetermined, as was done in past AAF deployments. This freed the principal investigators' time for other campaign-related activities without the worry of running out of flight hours before the end of the campaign. Instead we were able to fly nearly every day, outside of required "soft-down" and "hard-down" days. Flight patterns and purpose of the flights were still modified depending on the forecasted meteorological conditions. Since there were several HI-SCALE objectives, it was not necessary to fly only on shallow cumulus days.

4.2 Instruments

As expected for all field campaigns, some instruments were not working on select flights. These issues were usually resolved quickly. One aspect could have been prevented which was the high time-resolution moisture measurements needed to compute moisture fluxes. There apparently was a miscommunication among the AAF staff and the PIs about that instrument and consequently measurements were not collected during the first IOP of HI-SCALE. This measurement was not part of the post-flight de-brief. The PIs assumed that the measurements was being made and were not aware of the problem until the conclusion of the first IOP. This problem was not fixed until a few days passed into the second IOP of HI-SCALE. The lack of moisture fluxes affects one of the objectives of HI-SCALE to look at land-atmosphere interactions and how that relates to convection. In hindsight, the PIs should have been more diligent asking about the status of every specific measurement that was being made. A secondary issue was the size distribution measurements. The UHSAS worked well during the first IOP, but the data from the passive cavity aerosol spectrometer probe (PCASP) were not good. Both of these instruments measure aerosol size distribution, although the size range is somewhat different between the two instruments. The problem with PCASP, however, did not seriously impact HI-SCALE science. This demonstrated the importance of having redundant instruments for critical quantities.

4.3 Logistics

The G-1 aircraft operations were based at the Bartlesville Municipal Airport, which is about 150 km east of the SGP. It was chosen because no other viable options were available in the region at the beginning of the campaign. The distance between Bartlesville and the SGP site meant that time was required to ferry the aircraft to the primary sampling regions (~ 20 minutes one way). During the first IOP, this did not pose a significant problem since the relatively cool temperatures permitted an average flight duration of 3.5 hours (and as much as 4 h). Another advantage of the ferry is that it permitted the G-1 to sample a gradient of biogenic aerosols and precursors in the region. The Ponca City airport became available for the second IOP and a choice was made in May of where to base the G-1 for that IOP. It was clear that the AAF staff and technical director preferred the Bartlesville airport because of logistical issue related to packing and moving equipment associated with a change in location, and generally better accommodations in Bartlesville compared to Ponca City. The PIs decided to continue to use the Bartlesville airport as a matter of continuity and because it would be useful to have the same types of flight patterns during both IOPs. The PIs were aware that higher temperatures during the summer would impact aircraft operations but took a risk that temperatures would be close to normal. However, the temperatures during the second IOP were often higher than normal, which reduced the flight durations and led to earlier take-off times than would be optimal. Therefore, the flight paths during the second IOP were less than ideal to achieve the objectives of the campaign. The PIs adjusted the flight plans as well as they could to accommodate the shorter flight durations. In hindsight, the PIs would have chosen the Ponca City airport for the base of operations during the second IOP. That choice would have permitted more sampling in the vicinity of the SGP site since the ferry time to Bartlesville would have been eliminated.

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