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NOAA Air Resources Laboratory Atmospheric Turbulence and Diffusion Division Contribution to LAFE Field Campaign Report

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ARM CLIMATE RESEARCH FACILITY

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Acronyms and Abbreviations

AERI	atmospheric emitted radiance interferometer
AGL	above ground level
ARL	Air Resources Laboratory
ARM	Atmospheric Radiation Measurement
ATDD	Atmospheric Turbulence and Diffusion Division
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CIRES	Cooperative Institute for Research in Environmental Sciences
DOE	U.S. Department of Energy
ESRL	Earth System Research Laboratory
HRRR	high-resolution rapid refresh
IOP	Intensive Operational Period
LAFE	Land-Atmosphere Feedback Experiment
LES	large-eddy simulation
LST	land surface temperature
MOST	Monin-Obukhov Similarity Theory
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NSSL	National Severe Storms Laboratory
PNNL	Pacific Northwest National Laboratory
SGP	Southern Great Plains
sUAS	small unmanned aircraft systems
UTC	Coordinated Universal Time
UTSI	University of Tennessee Space Institute

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1.0 Summary

The Land-Atmosphere Feedback Experiment (LAFE) was conducted between 1 and 31 August, 2017 at the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) observatory. The main scientific goal of LAFE was to investigate feedbacks occurring between different land surface types and the overlying atmosphere to improve turbulence parameterizations in numerical weather prediction models. LAFE collaborators included scientists from the following institutions:

- Cleveland State University
- Cooperative Institute for Meteorological Satellite Studies (CIMSS)
- Cooperative Institute for Research in Environmental Sciences (CIRES)
- Leibniz University Institute of Meteorology and Climatology
- Marquette University
- NASA Goddard Space Flight Center
- National Center for Atmospheric Research (NCAR)
- National Severe Storms Laboratory (NSSL)
- NOAA Earth System Research Laboratory (ESRL)
- Pacific Northwest National Laboratories (PNNL)
- University of Hohenheim Institute of Physics and Meteorology
- University of Tennessee Space Institute (UTSI).

In addition to helping plan the scientific objectives of LAFE, collaborators deployed several lidars (i.e., temperature, water, vapor, and wind) and remote-sensing instruments (e.g., microwave radiometers, atmospheric emitted radiance interferometers [AERIs], etc.) to complement the suite of instrument platforms already present at the SGP site. The measurement platforms, as well as scientific objectives of LAFE, are summarized in Wulfmeyer et al. (2018). To complement these platforms, the NOAA Atmospheric Turbulence and Diffusion Division (ATDD) installed micrometeorological towers to continuously measure fluxes of momentum, sensible heat, latent heat, and CO_2 at 2 m and 10 m above ground level (AGL) at three sites during LAFE. Tower measurements also included temperature, humidity, wind speed and direction, pressure, rainfall, soil temperature, and soil moisture. The three micrometeorological towers were installed between 9 and 13 July, 2017 and were removed between 12 and 14 September, 2017. During the experiment, the footprint of Tower 1 included a mixture of soybean and grassland that transitioned to mature soybean crop during the second half of the experiment. Tower 2's footprint encompassed a field of grazed pasture, and Tower 3's footprint was a mature soybean crop. The meteorological and flux measurements from these towers were/are being used to:

1. Increase the spatial density of measurement platforms that were already available at the ARM facility and that were deployed during LAFE
2. Improve the characterization of surface fluxes around the SGP site

3. Explore the validity of applying Monin-Obukhov Similarity Theory (MOST) over different land surface types and improve knowledge of flux-gradient relationships
4. Provide initial conditions and be used for verification for large-eddy simulations (LES)
5. Evaluate numerical weather prediction models, e.g., the High-Resolution Rapid Refresh (HRRR), to identify and correct for biases within these models
6. Evaluate the role of low-level advection at each site, which would be present in the flux-divergence data sets obtained from the three towers.

The data sets from all three towers were mostly complete, but there were sporadic gaps in the data sets that occurred prior to the 1 August, 2017 start date of the experiment. For example, data gaps were present in middle July following a severe thunderstorm at the site on 14 July that resulted in wind gusts >20 m s^{-1} that toppled the solar panel at Tower 2. All solar panels and batteries were re-secured following this incident and prior to the official start of LAFE. As a result, no data gaps occurred during the official dates for LAFE.

In addition to these continuous measurements, ATDD participated in three intensive operational periods (IOPs). During the IOPs on 14 and 15 August, 2017, ATDD operated two small Unmanned Aircraft Systems (sUAS): a DJI S-1000 and MD4-1000. Both aircraft were outfitted with two iMet-XQ sensors to measure temperature, pressure, and humidity, and a FLIR infrared camera was installed on the DJI S- 1000 to sample land surface temperature (LST). The DJI S-1000 and MD4-1000 were flown simultaneously on both days every half hour between approximately 1730 and 0030 UTC along a southwest-northeast transect (Figure 1a). Both aircraft were flown in a box-like pattern, whereby the aircraft ascended to 100 m AGL and were flown northeastward approximately 500-600 m before ascending to 300 m and returning to the takeoff origin (Figure 1b). The DJI S-1000 was flown along a transect adjacent to Towers 2 and 3, whereas the MD4-1000 sUAS was flown starting approximately 500 m west of Tower 3 and flown northeastward toward Tower 4. Note that Tower 4 was operated by collaborators from the University of Hohenheim and was located within a field of un-grazed pasture. During the 17 August IOP, only the DJI S-1000 was flown. Over the three IOPs in which ATDD participated, ATDD performed 53 flights with the sUASs. ATDD also released six rawinsondes (two on 14 August, one on 15 August, and three on 17 August) during these IOPs to supplement rawinsondes routinely released from the SGP facility.

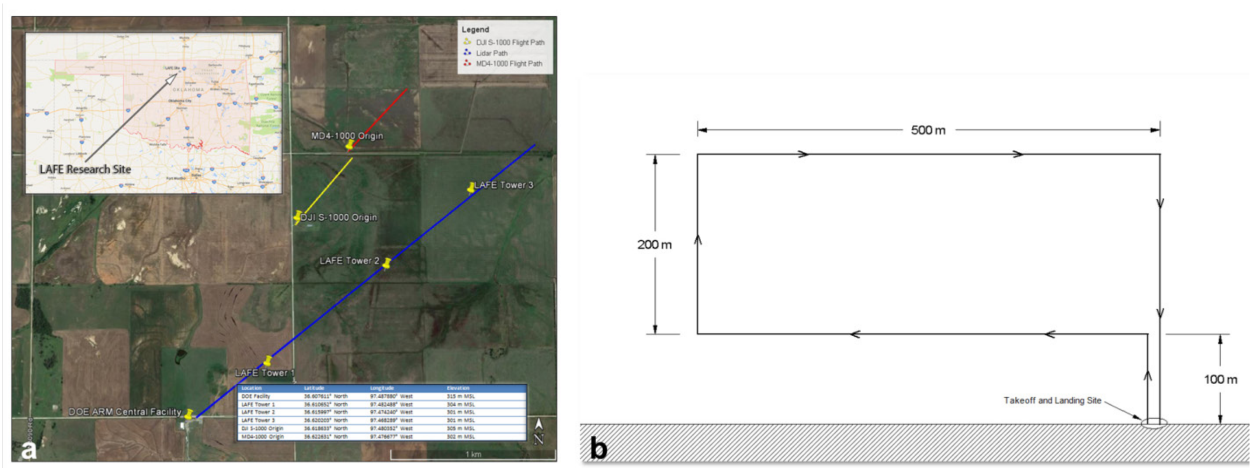

Figure 1. Flight path of the DJI S-1000 sUAS (yellow line) and MD4-1000 sUAS (red line) relative to the locations of the three ATDD micrometeorological towers (a) that were installed along a southwest to northeast transect (blue line). Inset image at the top left of panel (a) shows the location of the SGP site in northern Oklahoma, and the coordinates and elevation of each micrometeorological tower are shown in a table at the bottom right. Panel (b) shows the sUAS flight pattern relative to the takeoff and landing site.

2.0 Results

The measurements obtained from this component of LAFE are being used by other investigators for several different research topics relevant to the main LAFE goals. For example, the micrometeorological tower measurements are being used as inputs into LES and will also be used to evaluate state variables and fluxes obtained from the suite of boundary-layer profilers deployed during LAFE.

By themselves, however, the measurements that ATDD collected provide unique areas for research, including evaluating the heterogeneity of surface and near-surface meteorology and fluxes and exploring the validity of applying MOST relationships to different land surfaces. In this section, results from these two areas as well as avenues for future research are discussed.

2.1 Variability in Surface Characteristics during LAFE

August 2017 was uncharacteristically wet over northern Oklahoma, particularly during the early and middle part of the month when mean afternoon latent heat fluxes were ~300-350 W m^{-2} at all three of ATDD's micrometeorological towers (Figure 2). The latter half of August was more representative of conditions typically observed in the region, with drier conditions and larger afternoon sensible heat fluxes observed during this period. The IOPs ATDD conducted were during the middle of the month when mean daily sensible heat fluxes were increasing. The IOPs with the sUAS provide a unique opportunity to quantify the spatial variability in LST. To have confidence in the LST measurements from the infrared cameras installed on the sUAS and on the Piper Navajo aircraft operated by colleagues from UTSI, we performed intercomparisons between these measurements and the LST measurements obtained from the micrometeorological towers. Once we had confidence in the measurements from the infrared cameras, we used a conditional sampling technique developed by Lee et al. (2017) to compute heat fluxes using the sUAS (Figure 3). This technique is now being used to help quantify the spatial variability in LST and heat flux as well as the representativeness of the micrometeorological tower measurements.

In addition to mapping variations in LST and heat flux, the in situ measurements from the sUAS are providing important information about temperature and moisture fields over the lowest 300 m of the atmosphere. As the remote-scanning instruments deployed during LAFE start providing measurements starting at 100 m AGL, the meteorological measurements from the sUAS are helping us to close this gap in the measurements and will be used to provide a more complete view of the evolution in temperature and moisture fields over the entire depth of the boundary layer.

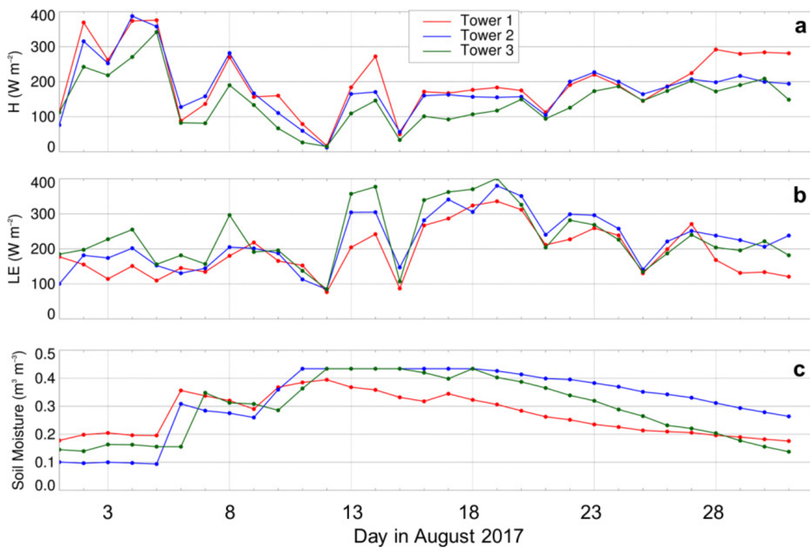

Figure 2. Mean afternoon (1800-2200 UTC) 10 m AGL sensible heat flux (a), 10 m AGL latent heat flux (b), and 5 cm soil moisture (c) obtained from grassland/soybean (Tower 1, red line), grassland (Tower 2, blue line), and soybean (Tower 3, green line).

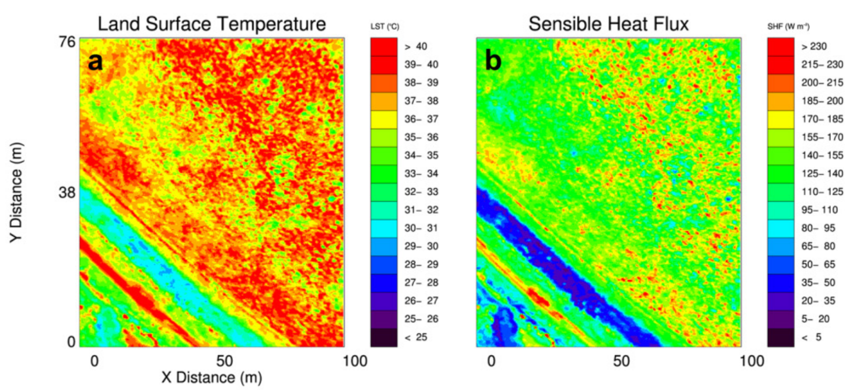

Figure 3. Example of heterogeneity in LST (a) and sensible heat flux (b), determined from the infrared camera during the DJI S-1000 sUAS flight at 1943 UTC on 17 August, 2017.

2.2 Flux-Gradient Relationships

Recent analyses have also focused on using the measurements that ATDD collected during LAFE to explore the validity of applying relationships from MOST to the different land surface types present within the LAFE domain. Deviations from MOST were noted. For example, in the case of normalized vertical velocity standard deviation scaled by friction velocity (i.e., $\frac{\sigma_w}{u_*}$) as a function of the stability parameter $\frac{z}{L}$, there are site-to-site differences in the similarity relationships among the three towers, with the largest differences occurring in the most unstable cases (i.e., $\frac{z}{L} < -5$) (Figure 4). Other MOST flux-gradient relationships will continue to be explored using these data sets, and new relationships will be developed. These relationships will be further tested and evaluated using LES that we will run over the upcoming months.

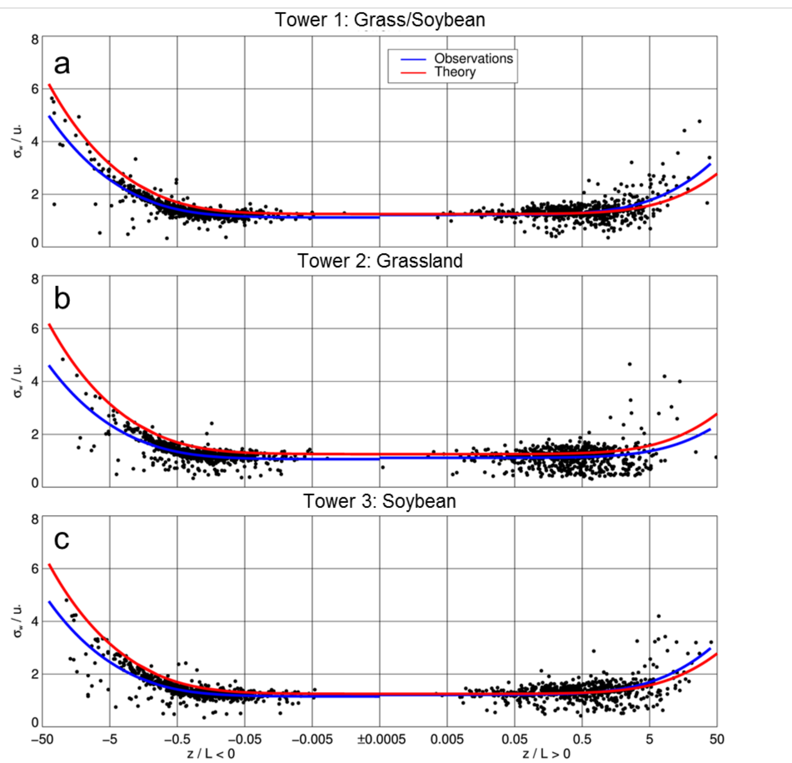

Figure 4. $\frac{\sigma_w}{u_*}$ as a function of $\frac{z}{L}$ over grassland/soybean (Tower 1, panel a), grassland (Tower 2, panel b), and soybean (Tower 3, panel c). Dots represent measurements; the blue line represents the best-fit line to the data, computed using least squares regression; and the red line indicates the theoretical best-fit curve derived from previous studies (i.e., Kaimal and Finnegan, 1994). The best-fit curves are of the form $\frac{\sigma_w}{u_*} = a_1(1 - a_2\frac{z}{L})^{\frac{1}{3}}$, where a_1 and a_2 are 1.25 and 3.0, respectively, for $\frac{z}{L} < 0$ and are 1.25 and 0.2, respectively, for $\frac{z}{L} > 0$, following Kaimal and Finnegan (1994). For Tower 1, when $\frac{z}{L} < 0$, $a_1 = 1.12$ and $a_2 = 2.17$; when $\frac{z}{L} > 0$, $a_1 = 1.22$ and $a_2 = 0.41$. For Tower 2, when $\frac{z}{L} < 0$, $a_1 = 1.06$ and $a_2 = 2.03$; when $\frac{z}{L} > 0$, $a_1 = 1.11$ and $a_2 = 0.17$. For Tower 3, when $\frac{z}{L} < 0$, $a_1 = 1.15$ and $a_2 = 1.75$; when $\frac{z}{L} > 0$, $a_1 = 1.21$ and $a_2 = 0.35$.

3.0 Publications and References

Publications

Wulfmeyer V, DD Turner, B Baker, R Banta, A Behrendt, T Bonin, WA Brewer, M Buban, A Choukulkar, E Dumas, RM Hardesty, T Heus, D Lange, TR Lee, S Metzendorf, T Meyers, R Newsom, M Osman, S Raasch, J Santanello, C Senff, F Späth, T Wagner, and T Weckwerth. 2018. "A new research approach for observing and characterizing land-atmosphere feedback." *Bulletin of the American Meteorological Society*, doi:10.1175/BAMS-D-17-0009.1.

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In-Text Citations

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Lee, TR, M Buban, E Dumas, and CB Baker. 2017. "A new technique to estimate sensible heat fluxes around micrometeorological towers using small unmanned aircraft systems." *Journal of Atmospheric and Oceanic Technology* 34 (9): 2103-2112, doi:10.1175/JTECH-D-17-0065.1.

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