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Atmospheric Boundary Layer-Wind Farm Interactions Field Campaign Report

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Acronyms and Abbreviations

ABL	atmospheric boundary layer
AERI	atmospheric emitted infrared interferometer
AERIoe	Atmospheric Emitted Radiance Interferometer Optimal Estimation Value-Added Product
AGL	above ground level
ARM	Atmospheric Radiation Measurement
AWAKEN	American WAKE ExperimeNt
CLAMPS	Collaborative Lower Atmosphere Profiling System
LLNL	Lawrence Livermore National Laboratory
MWR	microwave radiometer
NOAA	National Oceanic and Atmospheric Administration
NSSL	National Severe Storms Laboratory
OU	University of Oklahoma
PPI	plan position indicator
RMGC	Rolling Meadows Golf Club
SGP	Southern Great Plains
TROPoe	Tropospheric Optimal Estimation Retrieval Value-Added Product
USGS	United States Geological Survey
VAD	vertical azimuth display

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1.0 Summary

The American WAKE ExperimeNt (AWAKEN) was a field campaign in northern Oklahoma intended to analyze the potential influence of wind farms and their collective wakes on the atmospheric boundary layer (ABL), wind power production, and turbine structural loads. This report summarizes the deployment of instruments by the University of Oklahoma (OU), National Atmospheric and Atmospheric Administration National Severe Storms Laboratory (NOAA NSSL), and Lawrence Livermore National Laboratory (LLNL) during AWAKEN. Two Collaborative Lower Atmosphere Profiling Systems (CLAMPS) and LLNL ZephIR profiling lidars were co-deployed from October 3, 2022, to December 20, 2022 (winter campaign). At the end of the winter campaign, both ZephIR lidars were moved to different AWAKEN sites to be a part of a targeted wake study at the King Plains wind farm. The two CLAMPS were redeployed for a second observation period from July 1st, 2023, to September 28, 2023 (summer campaign; the ZephIR lidars were not co-located with CLAMPS).

The CLAMPS platforms integrate multiple remote-sensing instruments in a trailer for simultaneous data collection (Wagner et al. 2019). The two systems are maintained and operated by OU (CLAMPS1) and NOAA NSSL (CLAMPS2), respectively. Each platform includes a microwave radiometer (MWR; Rose et al. 2005), an atmospheric emitted infrared interferometer (AERI; Knuteson et al. 2004a, 2004b), and a Halo Photonics Doppler lidar (Pearson et al. 2009) along with an attached surface meteorological station. Both the MWR and AERI collected downwelling radiance information, in the microwave and infrared portions of the electromagnetic spectrum, respectively, and the data were then processed as described in the readme files using the Tropospheric Optimal Estimation Retrieval (TROPoe; known formerly as AERIoe; Turner and Löhnert 2014, Turner and Blumberg 2018) into profiles of temperature and moisture. The maximum range of the CLAMPS1 lidar is 7-10 km and closer to 12 km for the CLAMPS2 lidar, and both are capable of 18-m range gate resolution. One disadvantage of the scanning lidar is the inability to start measuring in range gates closest to the surface—lowest usable observations begin at approximately 60 m AGL. To resolve this data gap, we can use measurements from co-located continuous-wave ZephIR 300 profiling lidars when available.

Figure 1 is a map of the wind farms and CLAMPS and ZephIR sites in the AWAKEN domain. During the winter campaign, the LLNL ZephIR 300 773 profiling lidar (Z773) was sited alongside CLAMPS1 and the LLNL ZephIR 300 345 profiling lidar (Z345) was collocated with CLAMPS2. The CLAMPS1 and Z773 systems were deployed at the Rolling Meadows Golf Club (RMGC) near Covington, Oklahoma. This location was chosen because it is close to two wind farms: King Plains and Armadillo Flats. It was also a favorable location in terms of flat terrain, power availability, and low vegetation that did not obstruct the lidar beam. The RMGC site is located 1.9 km southwest of the closest turbine from King Plains (hub height = 89 m, rotor diameter = 127 m) and 2.2 km north of the closest turbine from Armadillo Flats (hub height = 90 m, rotor diameter = 116 m). Given the turbine-relative position of this site, wind-farm impacts can be monitored for situations with dominant flow from multiple wind directions. The CLAMPS2 and Z345 systems were placed at one of the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) atmospheric observatory extended facilities, ARM site E36, located 20 km northeast of the closest turbine at the Red Dirt wind farm (hub height = 87.5 m, rotor diameter = 125 m) and 12 km south of the closest wind turbine from Armadillo Flats (hub height = 80 m, rotor diameter = 100 m). Like RMGC, power was available with a flat surface and low vegetation coverage. A north-south transect can be made between this site and RMGC. If winds were northerly, this site could be subject to impacts from the Armadillo Flats wind farm,

but southerly flow is climatologically most frequent in northern Oklahoma. For southwesterly flow, the Red Dirt wind farm may also influence E36 observations. However, the light gray dots in Figure 1 east of Red Dirt indicate another wind farm under construction as of 2023. The turbines did progressively appear in the region over time, but they were not operational until the first quarter of 2024 (i.e., they were not in motion) and are unlikely to impact the measurements at E36.

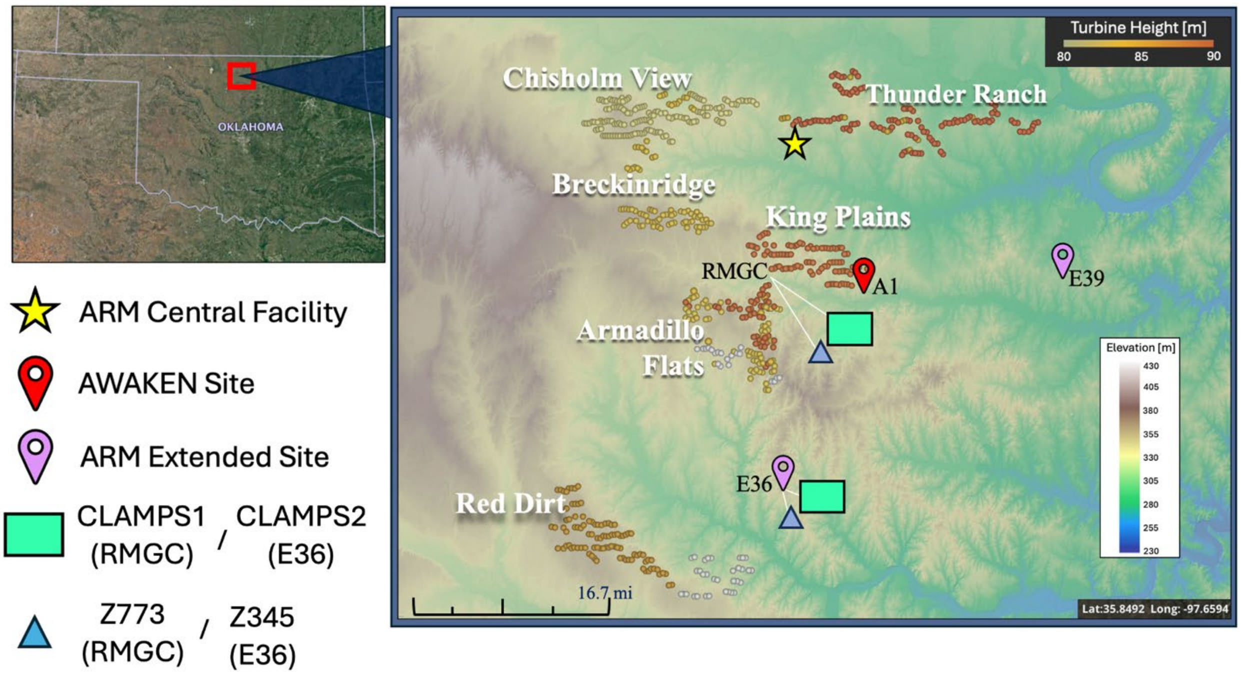

Figure 1. Satellite view of Oklahoma created in Google Earth (left) with a zoomed-in version of the AWAKEN domain containing terrain elevation information (right). Terrain and turbine height information came from the United States Geological Survey (USGS). Zoomed-in map represents the sites used for the deployment of the CLAMPS platforms and ZephIR 300 profiling lidars for two campaigns as described in the text. There are a couple of areas of turbines that were under construction and not yet operational during the deployment of CLAMPS and the profiling lidars (light gray symbols).

For the winter and summer campaigns, the CLAMPS Halo lidars were set to collect 70° elevation angle plan position indicator (PPI) scans every 10 or 15 minutes that were later processed into vertical azimuth display (VAD) measurements for horizontal wind speed (*ws*) and wind direction (*wd*) information. In between the PPI scans, CLAMPS lidars stared vertically to provide vertical velocity (*w*) observations. They operated with 30-m range gates. Many data collection periods during the winter campaign were partially to fully obstructed due to condensation on the CLAMPS lidar lens from dew or low fog, so the summer deployment proved critical to obtain a broader data set. However, during the summer campaign in 2023, the CLAMPS1 lidar encountered issues in correctly processing *wd* information due to technical difficulties (the lidar's azimuthal encoder was unable to detect the scanner's relative position in azimuth, which was the result of lubricant obscuring the home position beacon following repairs by the vendor to address the lens fogging issues identified during the winter campaign). Therefore, CLAMPS1 *wd* data are only available during the winter campaign, but this issue did not impact CLAMPS1 *ws* data. The Z773 and Z345 lidars output both ~15-second high-frequency data and 10-minute averaged wind speed *ws*, estimated vertical wind speed *w*, and wind direction *wd*. These lidars were programmed to take measurements every 10 m from 10-80 m (except instead of 40 m, 38 m which is a fixed reference measurement and cannot be changed by the user), 110, 140, and 180 m. These heights were chosen not only to encompass the altitudes CLAMPS cannot reach, but to obtain high-vertical-resolution information about the wind profile at turbine rotor-disk heights. A summary of the available data is presented in Figure 2.

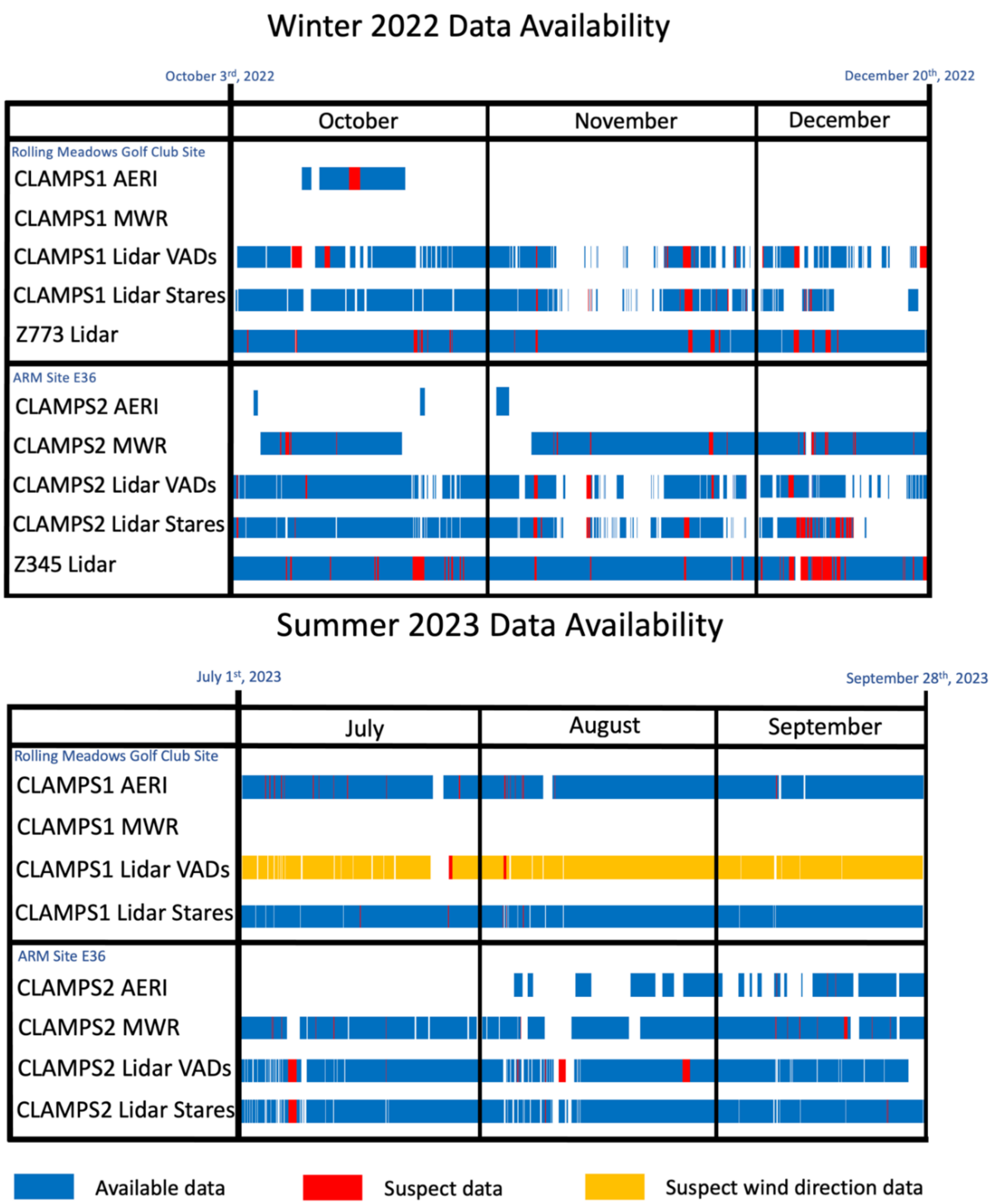

Figure 2. Data availability for the AWAKEN ZephIR 300 profiling lidar and CLAMPS winter 2022 and summer 2023 campaigns at the Rolling Meadows Golf Club and ARM E36 sites.

2.0 Results

Figure 3 shows monthly wind roses for AWAKEN and nearby ARM sites throughout the winter campaign. Only data from the range gate closest to the turbine hub height of Armadillo Flats (90 m) was used, which was slightly different between all the lidars as indicated in the plots. As anticipated, the winds were primarily southerly, southwesterly, or southeasterly at each site. Winds from these directions were consistently the strongest, peaking at each site in October. During this month, both RMGC and ARM site E39 recorded the strongest wind speeds of the four sites. In November, this was the case again for E39, but RMGC yielded wind speeds in the 0-5 m s^{-1} range, at least when flow was directly southerly. Meanwhile, the wind speeds were similar between each site in December. We are currently investigating if/how the differences in wind climatology at the four sites can be explained by the wind farms with a focus on nights with pronounced low-level jets. A similar analysis is currently also being conducted for the summer campaign, but the erroneous CLAMPS1 wind direction data will require corrections that may be possible employing data from other AWAKEN sites.

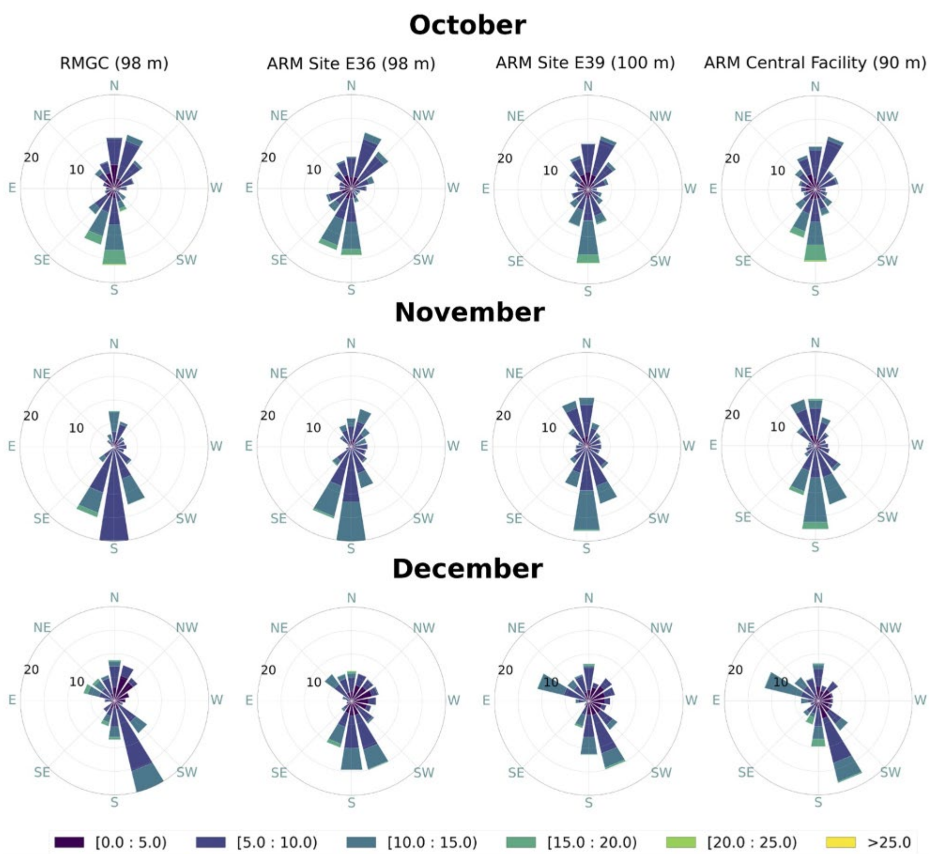

Figure 3. Wind roses of lidar data from RMGC and ARM sites E36, E39, and the ARM Central Facility from the winter campaign (2022-10-03 to 2022-12-20). Analyzed here is the range gate from each lidar that is closest to wind turbine height of the Armadillo Flats turbine.

An example of CLAMPS and ZephIR lidar wind observations at the Rolling Meadows Golf Club and ARM E36 site is presented in Figure 4. Combining the two lidar systems provides high-resolution wind profiles from the surface to heights above the turbine rotor disks. The scatterplots included in Figure 4 show that hub-height wind speeds observed with both systems overall agree very well. For this comparison, a rolling, 15-minute average was performed on the 15-second output from the RMGC site's Z773 lidar to provide data matching the temporal resolution of the CLAMPS1 lidar VAD data. CLAMPS1 VAD timestamps were taken to represent the center of the averaging interval. The same operation was executed on the E36 site's Z345 data, except a 10-minute averaging time was applied to match the CLAMPS2 lidar 10-minute resolution. Averaging the 15-second instantaneous ZephIR 300 data makes it more comparable to the wind profiles based on CLAMPS VADs; however, CLAMPS1 and CLAMPS2 wind profiles are not equivalent to true 15-min or 10-min averages. They are based on PPI scans occurring every 10 to 15 minutes. Each PPI scan lasts 40-60 seconds, meaning CLAMPS data are based on a sample collected over a shorter time window than the ZephIR data. This comparison provides an opportunity to compare the representation of mean winds based on two different lidar scan configurations that are commonly used. With a few exceptions, both sites show good agreement between the CLAMPS lidar and ZephIR 300 lidar; the correlation values are high, and the slope values are close to one.

As discussed in Jordan et al. (2024), additional data analysis products targeting the estimation of boundary-layer heights and optimal estimation of wind speed throughout the boundary layer are currently being generated. Further scientific analysis of the data focuses on identifying the role of the wind farms on ABL structure, on low-level jet dynamics, and on convection initiation in the AWAKEN domain.

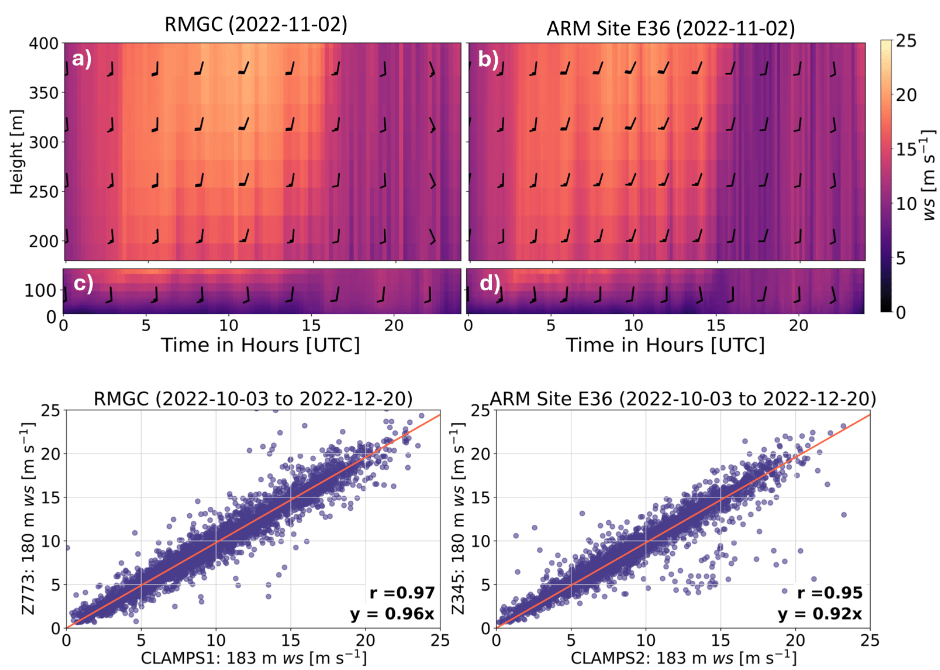

Figure 4. Combined analysis of *ws* data from the ZephIR 300 lidars and CLAMPS lidars. Panels (a) and (b) show time-height cross-sections of CLAMPS wind speed observations with wind barbs overlaid for 2 November 2022. Panels (c) and (d), showing the ZephIR lidar wind speed observations in a similar way, demonstrate how the two lidars can be combined at each site to create a complementary profile down to the surface. The left column (a, c) shows data from RMGC, collected by CLAMPS1 and Z773. The right column (b, d) shows data from E36, collected by CLAMPS2 and Z345. The scatterplots beneath the four panels show a comparison of CLAMPS and ZephIR lidar wind speed data at the measurement height closest to 180 m for the entire winter campaign.

3.0 Publications and References

3.1 Data Sets Collected at Site E36

AWAKEN 2023 NOAA CLAMPS2 AERI TROPoe Retrievals: https://doi.org/10.5439/2349337

AWAKEN 2023 NOAA CLAMPS2 MWR TROPoe Retrievals: https://doi.org/10.5439/2356788

AWAKEN NOAA CLAMPS2 Doppler Lidar VAD Data: https://doi.org/10.5439/2361040

AWAKEN NOAA CLAMPS2 Doppler Lidar Vertical Stare Data: https://doi.org/10.5439/2368747

AWAKEN LLNL ZephIR lidar data: https://a2e.energy.gov/ds/awaken/se36.lidar.z01.00

3.2 Data Sets Collected at Rolling Meadows Golf Course

AWAKEN 2023 OU CLAMPS1 AERI TROPoe Retrievals: https://doi.org/10.5439/2361037

AWAKEN OU CLAMPS1 Doppler Lidar VAD Data: https://doi.org/10.5439/2361039

AWAKEN OU CLAMPS1 Doppler Lidar Vertical Stare Data: https://doi.org/10.5439/2346006

AWAKEN LLNL ZephIR lidar data : https://a2e.energy.gov/ds/awaken/rmgc.lidar.z01.00

3.3 Publications

Jordan, AM, EN Smith, PM Klein, JG Gebauer, and S Wharton. 2024. "Probing the atmospheric boundary layer with integrated remote-sensing platforms during the American WAKE Experiment." *Journal of Renewable Energy* (pending revisions).

3.4 Presentations

Jordan, AM. 2022. "A Preliminary Examination of Kinematic Wind Farm Effects on the Planetary Boundary Layer during the 2022 American WAKE ExperimeNt." Presented at University of Oklahoma seminar.

Jordan, AM. 2023. "Validation of Boundary Layer Height Detection Techniques for Southern Great Plains US Summer Cases." Presented at the 103rd annual meeting of the American Meteorological Society.

Jordan, AM. 2023. "An Early Look into Boundary Layer-Wind Farm Interactions from the American WAKE ExperimeNt." Presented at University of Oklahoma seminar.

Jordan, AM. 2023. "An Early Look into Boundary Layer-Wind Farm Interactions from the American WAKE ExperimeNt." Presented at the North American Wind Energy Academy/WindTech 2023 Conference.

Jordan, AM, PM Klein, EN Smith, S Wharton, T Bell, J Gebauer, L Bunting, and M Puccioni. 2024. "A First Look into Boundary Layer-Wind Farm Interactions from the American Wake Experiment." Presented at the 104th Annual Meeting of the American Meteorological Society.

Abraham, A, E Maric, M Puccioni, A Jordan, S Letizia, N Bodini, N Hamilton, S Wharton, PM Klein, EN Smith, and P Moriarty. 2024. "Wind Plant Impacts on Planetary Boundary Layer Height." Presented at the 104th AMS Annual Meeting of the American Meteorological Society.

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Pearson, G, F Davies, and C Collier. 2009. "An analysis of the performance of the UFAM pulsed doppler lidar for observing the boundary layer." *Journal of Atmospheric and Oceanic Technology* 26(2): 240–250, https://doi.org/10.1175/2008JTECHA1128.1

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Turner, DD, and U. Löhnert. 2014. "Information content and uncertainties in thermodynamic profiles and liquid cloud properties retrieved from the ground-based atmospheric emitted radiance interferometer (AERI)." *Journal of Applied Meteorology and Climatology* 53(3): 752–771, https://doi.org/10.1175/JAMC-D-13-0126.1

Turner, DD, and WG Blumberg. 2018. "Improvements to the AERIoe thermodynamic profile retrieval algorithm." *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 12(5): 1339–1354, https://doi.org/10.1109/JSTARS.2018.2874968

Wagner, TJ, PM Klein, and DD Turner. 2019. "A new generation of ground-based mobile platforms for active and passive profiling of the boundary layer." *Bulletin of the American Meteorological Society* 100(1): 137–153, https://doi.org/10.1175/BAMS-D-17-0165.1

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