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American WAKE Experiment (AWAKEN) Field Campaign Report

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Executive Summary

The American WAKE experimeNt (AWAKEN) was a large-scale, international collaborative field campaign funded primarily by the U.S. Department of Energy (DOE) Wind Energy Technologies Office. Its main purpose was to gather detailed observations of wind farm-atmosphere interactions to improve understanding of wind farm physics, validate and improve simulation tools, lower uncertainties in wind farm modeling, understand environmental impacts, and ultimately reduce the cost and increase the reliability of wind energy systems. The campaign specifically focused on seven testable hypotheses that include characterizing wind turbine and wind farm wake effects, wind farm blockage, turbulent mixing, structural loading impacts, local environmental impacts, and testing wind farm control technologies. AWAKEN was a highly collaborative effort involving numerous agencies, including: DOE, through the Wind Energy Technologies Office and the Office of Science Atmospheric Radiation Measurement (ARM) User Facility, the U.S. Department of Commerce through the National Oceanic and Atmospheric Administration, many American universities, and internationally funded collaborators from Germany and Brazil.

The campaign was located in northern Oklahoma, specifically in a region near DOE's ARM Southern Great Plains (SGP) long-term atmospheric observatory. The campaign leveraged the extensive existing ARM infrastructure, historical data, and ongoing measurements, particularly from the ARM SGP Central Facility. Additional AWAKEN-specific instrument sites were deployed around five wind farms in the area, several kilometers south of the ARM facility. The ARM Mobile Facility, AMF3, was also used at these sites. The AWAKEN field campaign began instrument deployment in September 2022 and ran through July 2025. Specific intensive operating campaigns, such as the mobile lidar and aircraft measurements, were conducted in August and September 2023, and tethersonde measurements occurred during October 2024.

Key observations and initial results from AWAKEN provide critical insights into wind farm physics and environmental impacts. The campaign saw the first land-based, long-duration use of X-band dual-Doppler radar systems for wind energy applications, capable of reconstructing wind fields over an approximate 35x35-km domain, which documented various wind phenomena including a tornadic event and thunderstorm outflows. These radar observations also showed that the wake of one wind farm can extend at least 15 km downstream under specific stable atmospheric conditions. Preliminary analyses of atmospheric boundary-layer interactions identified a pattern of stronger lower-atmospheric mixing at near-farm sites compared to far-field locations. Initial observations from sonic anemometers indicated that near-surface turbulence kinetic energy within the wind farm was significantly modified, being more than 50% larger at an in-farm site compared to an upwind site in stable conditions. Furthermore, observations of nocturnal low-level jets revealed key findings about how low-level jet height impacts wake recovery, with faster recovery largely occurring due to enhanced entrainment of vertical momentum flux.

AWAKEN was also notable for the first large-scale deployment of thermodynamic profilers around wind farms, the temperature profiles of which substantiated the theory of nighttime warming of the surface layer in turbine wakes by correlating with the mixing of warm air aloft enabled by wake-added turbulence. Lidar measurements were used to characterize the variability of wake mean velocity and turbulence intensity under different atmospheric stability regimes, showing significant variability in the

downstream evolution of wind farm wakes depending on incoming wind shear. Dual-Doppler lidar measurements also suggested that wind farm blockage can cause standard ground-based lidar wind profiling methods to underestimate inflow wind speed, particularly under stable conditions, due to persistent horizontal gradients in the flow upwind of the wind farm. Finally, analysis indicated that even in regions with relatively simple topography, local terrain features can induce significant spatial variability and flow acceleration, especially under certain atmospheric conditions, adding complexity and challenging the observation of wind farm-specific phenomena. This extensive data set is now being used for validating and improving various simulation tools, including through international benchmark studies. The data is publicly available at the DOE Wind Data Hub and the authors encourage usage by the atmospheric science and wind energy community for further study.

Acknowledgements

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Acronyms and Abbreviations

ABL	atmospheric boundary layer
AERI	atmospheric emitted radiance interferometer
AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
ASSIST	Atmospheric Sounder Spectrometer by Infrared Spectral Technology
AWAKEN	American WAKE Experiment
DOE	U.S. Department of Energy
FLORIS	Flow Redirection and Induction in Steady State
LLJ	low-level jet
NOAA	National Oceanic and Atmospheric Administration
RANS	Reynolds-averaged Navier-Stokes
RMSD	root-mean-square difference
SCADA	supervisory control and data acquisition
SGP	Southern Great Plains
TKE	turbulence kinetic energy
TROPoe	Tropospheric Optimal Estimation Retrieval Value-Added Product
UTC	Coordinated Universal Time
WRF	Weather Research and Forecasting Model

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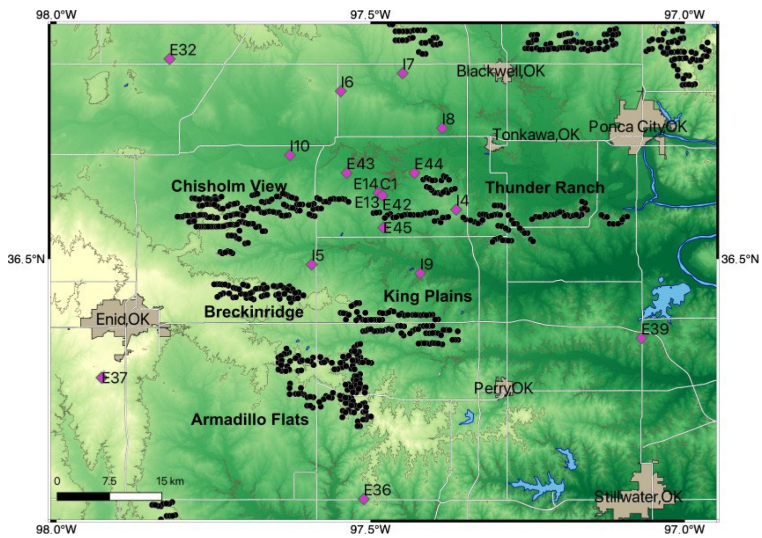
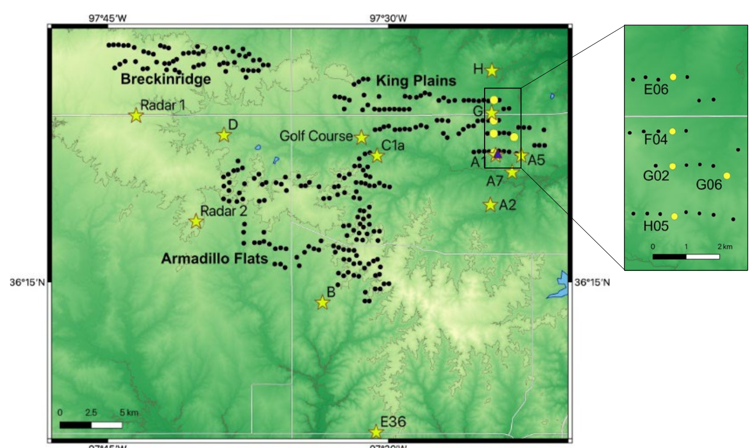
1.0 Background

The American WAKE experimeNt (AWAKEN) was one of the largest field campaigns to date focused on wind farm-atmosphere interactions. It took place from November 2022 through July 2025 within five wind farms located near the U.S. Department of Energy's (DOE's) Atmospheric Radiation Measurement (ARM) User Facility Southern Great Plains (SGP) observatory in northern Oklahoma, as shown in Figure 1a (Moriarty et al. 2020). The campaign gathered an unprecedented data set including both atmospheric observations and wind farm operational data.



(a) ARM SGP facilities and nearby wind farms (black dots).



(b) Instrumentation sites (stars) and instrumented turbines (circles) south of the ARM SGP Central Facility.

Figure 1. Instrument locations and turbine locations in the AWAKEN study region.

The campaign features a suite of instrumentation that ranges in scale and fidelity. This includes a large number of scanning and profiling lidars, X-band radars, sonic anemometers, thermodynamic profilers, meteorological stations, radiosondes, and tethersondes deployed across 13 ground-based sites and on multiple turbines (see Figure 1b). Mobile platforms, such as a truck-mounted lidar and a research aircraft, were also used, primarily for characterizing wind farm wakes.

The campaign was strategically located in northern Oklahoma to leverage the existing observational facilities of DOE's ARM SGP observatory. This location provides access to long-term atmospheric measurement records and a broad spatial area for instrument deployment and comparison. AWAKEN also used instruments from the third ARM Mobile Facility (AMF3) at three different sites within the campaign (Table 1).

Table 1. ARM instrument deployments at sites A1, A2, and H during the AWAKEN campaign.

Site	Instrument (ARM Name)	Name on Wind Data Hub	Deployment Period
A1	Halo XR+ scanning lidar (DL)	sa2.lidar.z01 / arm.lidar.sgp_s5	12/2022–01/2024
	AERI thermodynamic profiler (AERI)	arm.aeri.sgp_s4	11/2022–01/2024
	Microwave radiometer (MWR)	arm.mwr.sgp_s4	09/2022–01/2024
	Solar and Infrared Radiation Station (SIRS)	arm.sirs.sgp_s4	04/2023–01/2024
	Total Sky Imager (TSI)	arm.tsi.sgp_s4	11/2022–01/2024
	Surface meteorological station (MET)	On ARM data portal only	04/2023–09/2023
	Eddy Correlation Flux (ECOR)	On ARM data portal only	04/2023–09/2023
	Infrared thermometer (IRT)	On ARM data portal only	04/2023–09/2023
A2	Halo XR scanning lidar (DL)	sa2.lidar.z01 / arm.lidar.sgp_s5	12/2022–09/2023
H	Halo XR+ scanning lidar (DL)	sa2.lidar.z01 / arm.lidar.sgp_s5	12/2022–01/2024
	AERI thermodynamic profiler (AERI)	arm.aeri.sgp_s6	09/2022–01/2024
	Ceilometer (CEIL)	arm.ceil.sgp_s6	11/2022–09/2023
	Microwave radiometer (MWR)	arm.mwr.sgp_s6	11/2022–01/2024
	Eddy Correlation Flux (ECOR)	On ARM data portal only	04/2023–09/2023
	Automatic Weather Station (MAWS)	On ARM data portal only	04/2023–09/2023
	Radiosonde (SONDE)	On ARM data portal only	05/2023, 07/2023–08/2023

An example of the ARM AMF-3deployment is shown in Figure 2, with multiple instruments installed on top of a seatainer located at site A1.

Figure 2. ARM AMF3 instruments deployed south of the King Plains wind farm.

Partners in the field campaign included:

- DOE national laboratories: National Renewable Energy Laboratory (as lead institution), Sandia National Laboratories, Pacific Northwest National Laboratory, and Lawrence Livermore National Laboratory.
- Universities: University of California-Berkeley, Carl von Ossietzky University at Oldenburg, Cornell University, Ecole Polytechnique Federale de Lausanne, University of Texas at Dallas, University of Oklahoma, Oklahoma State University, Texas Tech University, University of Colorado-Boulder, Johns Hopkins University, Universidade de Sao Paulo, and Technische Universitat Braunschweig.
- Government/research institutions: ARM SGP site and mobile user facility, National Oceanic and Atmospheric Administration (NOAA) Chemical Sciences Laboratory and National Severe Storms Laboratory, Cooperative Institute for Research in Environmental Sciences, ForWind – Center for Wind Energy Research, and Fraunhofer Institute for Wind Energy Systems.
- Industrial partners: ENGIE, GE Vernova, Enel Green Power, and NextEra Energy.

AWAKEN was designed to address seven testable hypotheses identified as key research questions (Moriarty et al. 2024). The highest-priority science goal was the improved characterization and modeling of wind turbine and farm wakes, but the campaign also focused on wind farm blockage effects, turbine loading impacts, local environmental impacts, and the influence of larger-scale dynamic atmospheric events.

A strong emphasis was placed on data management and broad public dissemination of the collected observations. Data are stored and made available through the ARM Data Center and the DOE Wind Data Hub (U.S. Department of Energy 2025), maximizing their utility for the broader atmospheric science and wind energy research communities.

2.0 Notable Events or Highlights

Over the course of the observational campaign, some notable events from the AWAKEN project include:

Large-scale wind farm flows: The deployment of X-band dual-Doppler radar systems represents the first overland long-duration use of this technology in this configuration. These radars can reconstruct wind fields over a large domain (approximately 35x35 km) to document various wind phenomena at diverse scales, from regional flows to individual turbine wakes. Of particular interest were observations of a tornadic event propagating through the AWAKEN wind farms and several thunderstorm outflows, as shown in Figure 3. Technology advancements in these radars have led to a marked increase in data availability.

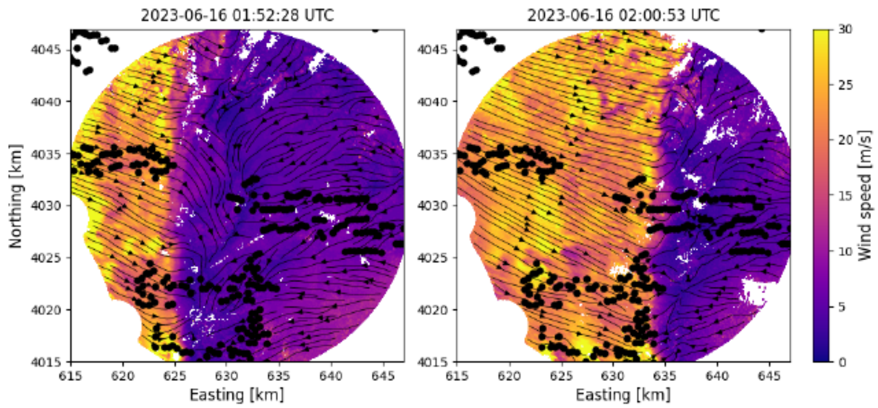


Figure 3. Thunderstorm outflow propagating through the AWAKEN wind farms, showing a 30 m/s wind speed change across the sampled region at an elevation near hub height. Frames are 8.5 minutes apart. Black dots represent wind turbines, and streamlines indicate wind direction.

Atmospheric boundary-layer (ABL) interactions: ABL characteristics and interactions were studied by comparing data collected at "near-farm" and "far-field" sites (Jordan et al. 2024; examples of which are shown in the schematic of Figure 4). Preliminary analyses identified a pattern of stronger lower-atmospheric mixing at a near-farm site compared to a far-field site, which aligns with expectations for the near-farm location. However, unexpected relative wind speeds at the near-farm site during the winter and a lack of sensitivity of ABL height estimates to flow direction suggest a complex relationship between wind farms and ABL properties that warrants deeper investigation.

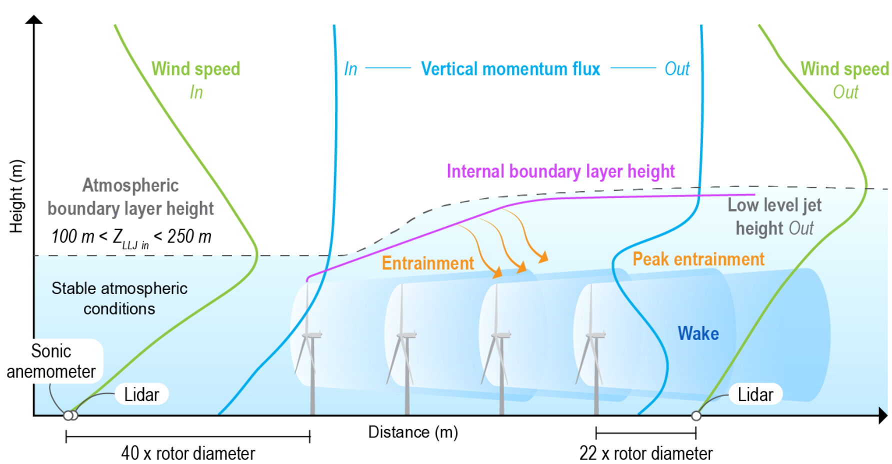


Figure 4. Examples of wind interactions with the ABL (Krishnamurthy et al. 2025).

Turbulence characteristics in the ABL were also modified by the wind farms as evidenced by near-surface turbulence kinetic energy (TKE) at site G (within the wind farm) being more than 50% larger than at site A5 (upwind of the wind farm for southerly wind conditions) in stable conditions, based on initial observations from sonic anemometers (Figure 5). Specific focus was also given to characterizing wind turbine wakes during the occurrence of nocturnal low-level jets (LLJs), with observations revealing key findings about how LLJ height impacts wake recovery (Krishnamurthy et al. 2025). TKE was also modified above the rotor layer, and faster wake recovery occurred largely because of enhanced entrainment of vertical momentum flux. Stable conditions showed larger deviations in momentum flux downwind, indicating enhanced vertical momentum transfer due to the wind farm.

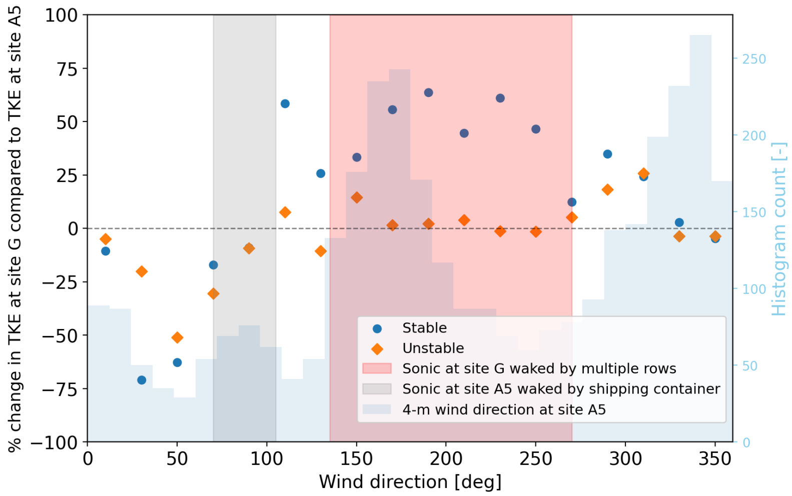


Figure 5. TKE differences between sites A5 and G as a function of wind direction.

Remote sensing of temperature: AWAKEN hosted the first large-scale deployment of thermodynamic profilers around wind farms. Thermodynamic profilers combine ground-based observations of the downwelling infrared spectral radiance from ASSIST-II passive spectroradiometers (Michaud-Belleau et al. 2025) with the physical retrieval algorithm TROPoe (Turner and Blumberg 2019) to estimate temperature and humidity profiles across the atmosphere. Thermodynamic profiling at AWAKEN used most of the methods developed during the ARM atmospheric emitted radiance interferometer (AERI) program (Mlawer and Turner 2016). ARM and Oklahoma State University also performed about 100 radiosonde launches from site H that provided an invaluable data set to benchmark the thermodynamic profiles obtained through remote sensing. In particular, by comparing the temperature estimated by ARM's Tropospheric Optimal Estimation Retrieval Value-Added Product (TROPoe) from the Atmospheric Sounder Spectrometer by Infrared Spectral Technology (ASSIST) deployed at site G with the observations from radiosondes launched at site H (Figure 6), it is possible to quantify the magnitude of the error in the thermodynamic profiles. In general, the temperatures provided by the two methods agree remarkably well, with a root-mean-square difference (RMSD) below 1˚C at ground level and at hub height (z = 90 m). The discrepancy is seen to slightly increase at 1,000 m above the ground, where differences of up to 3˚C can occur. This is mostly related to the poorer vertical resolution of TROPoe moving away from the instruments but also possibly to the drift of radiosondes from the launch site.

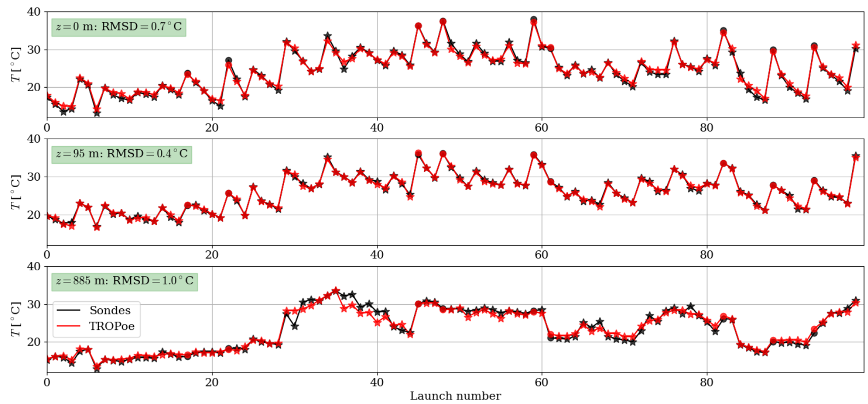


Figure 6. Temperature recorded at different heights by radiosondes and estimated TROPoe for all the radiosonde launches at site H. Stars indicate nighttime (00-12 UTC) data while circles indicate daytime (12-24 UTC) data.

Local temperature changes: Observations of temperature upwind and downwind of the wind farms revealed slight modifications of the temperature profiles near the ground depending on the downstream distance from the wind farms. Figure 7 shows the mean temperature difference from the thermodynamic profiling systems at sites G and C1a during stable conditions. The analysis included 30-minute-averaged thermodynamic profiles from May to October 2023 that were conditionally averaged as a function of the mean wind direction and height above the ground. The alternate pattern of temperature difference appears to be correlated with the number of turbines likely to generate wakes that impact the two sites. More specifically, when site G experienced more wakes, the layer of air below 200 m was warmer than at site C1a, and vice versa. The nighttime warming of the surface layer in the wake of turbines was reported by experimental (Rajewski et al. 2013, Smith et al. 2013, Wu and Archer 2021, Zhou et al. 2012) and numerical (Miller and Keith 2018, Wu et al. 2023, Xia et al. 2019) studies, and related to the mixing of warm air aloft enabled by the wake-added turbulence. However, the AWAKEN data set may be the first collection of height-resolved temperature observations that substantiates this theory.

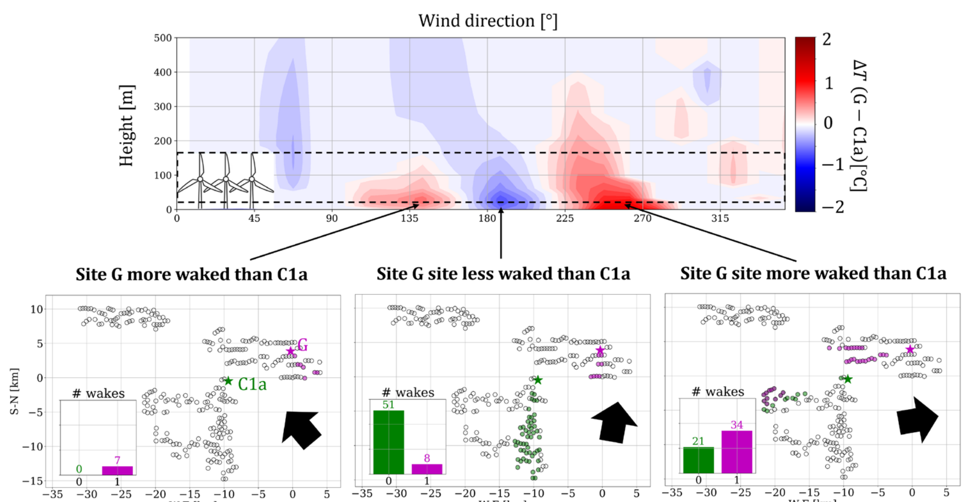


Figure 7. Mean temperature differences between sites G and C1a as a function of wind direction and height above the ground during stable conditions. The figure includes 30-minute-averaged thermodynamic profiles from May to October 2023.

International benchmark studies: AWAKEN data have been used to establish international benchmark studies within the International Energy AgencyWind Task 57. The first benchmark focused on wind farm wakes, aiming to assess and improve the accuracy of simulation tools using the AWAKEN observations. Data from days that satisfy specific atmospheric and turbine operational criteria have been selected for these benchmarks (see Bodini et al. 2024).

3.0 Results

AWAKEN generated a wealth of observational data to study wind farm-atmosphere interactions. These observations, collected using a variety of instruments, including lidars, radars, meteorological towers, flux stations, and turbine supervisory control and data acquisition (SCADA) systems, have yielded several key initial results and insights into wind characteristics, turbine and wind farm wakes, blockage effects, and interactions with the ABL.

The following summarizes research results derived from AWAKEN observations:

Site wind characteristics: Analysis of long-term observational data from the nearby ARM SGP observatory characterized the winds near the AWAKEN site. The site experiences high wind shear and veer events, including a large number of nocturnal LLJs that predominantly occur when wind blows from the south, as seen in Figure 8. Significant nocturnal wind veer was observed, where southerly wind near the surface becomes westerly aloft. Wind speed at turbine hub height (89 m) can be predicted from 10-m data, with varying biases depending on atmospheric stability. The daily variation of the ABL height has also been evaluated using vertically pointing, scanning pulsed Doppler lidar data, showing agreement with previous literature and the daily cycle of vertical velocity variance.

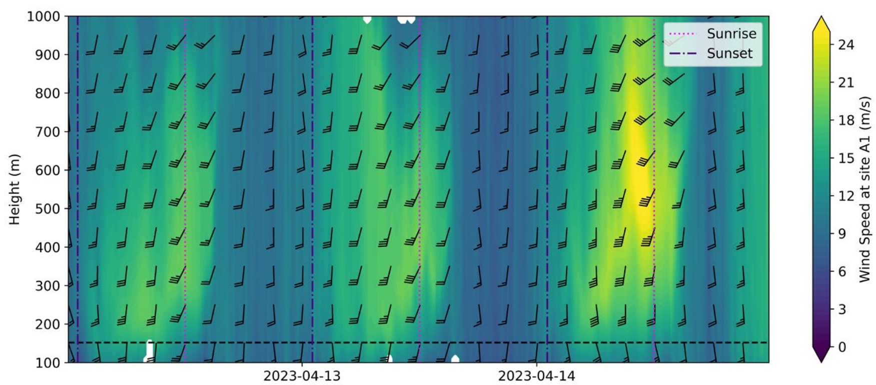


Figure 8. Plot of multiple diurnal cycles of lidar observations at AWAKEN site A1 with the presence of nocturnal LLJs.

Turbine and wind farm wakes: Lidar measurements of isolated wakes were used to characterize the variability of wake mean velocity and turbulence intensity under different atmospheric stability regimes and rotor thrust coefficients. Observations indicate that the downstream evolution of wind farm wakes shows significant variability depending on incoming wind shear. Dual-Doppler radar measurements over a large range (> 30 km) captured the region between wind farms. These measurements showed that the wake of one wind farm extends at least 15 km downstream under specific easterly wind and stable atmospheric conditions, as seen in the example shown in Figure 9. On average, over all conditions, the wake wind speed increased but plateaued at about 90% of the freestream speed within the first 10 km downstream. The velocity distribution across the width of the wind farm wake initially showed a clear signature of the farm layout, which smoothed out downstream, suggesting that spanwise momentum transfer (from the sides of the wind farm) is a key mechanism in wind farm wake development and recovery (Abraham et al. 2024).

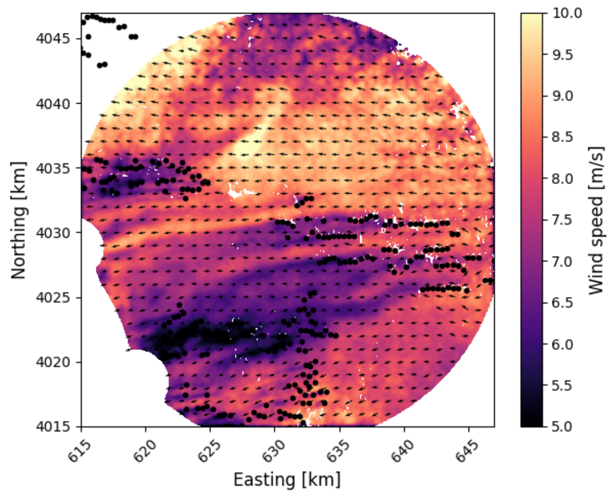


Figure 9. Example of a radar velocity field captured during stable atmospheric conditions showing the wake of King Plains (black dots on eastern side) impinging on Armadillo Flats (black dots on southern side).

Blockage effects: Dual-Doppler lidar measurements, configured as virtual towers, were conducted south of the leading-row turbines in the King Plains wind farm to characterize inflow and assess possible upwind blockage effects (Newsom et al. 2024), which is a slowing of the wind speed upstream of the wind farm. Blockage is often underrepresented in wind farm prediction models, making these observations useful for model improvement. Also, comparisons of these virtual tower results to collocated lidar wind profiling data revealed differences, particularly under stable conditions where the profiler wind speeds were about 22% lower than the virtual tower near hub height, as highlighted in Newsom et al. 2024. These results suggest persistent horizontal gradients due to blockage from the wind farm, which can lead to biased estimates using standard ground-based lidar wind profiling methods. This implies that wind farm blockage, in addition to lowering the overall potential wind farm energy production, can also cause standard lidar profiling to underestimate inflow wind speed.

Terrain-induced spatial variability, even in simple terrain: Analysis of long-term observations, including dual-Doppler radar and lidar data, combined with numerical simulations, indicates that even in regions with relatively simple topography like the AWAKEN site, local terrain features can induce significant spatial variability and flow acceleration (Radünz et al. 2025). This is particularly noticeable under certain atmospheric conditions, such as stable boundary layers or during LLJ events. These terrain effects are important to understand because they can add complexity and make it challenging to isolate and quantify phenomena purely attributable to wind farm blockage or wakes using observations alone.

4.0 Future Research Opportunities

As for future research opportunities, the observational data set collected during AWAKEN is one of the largest and most comprehensive of its kind, providing critical data for understanding complex wind farm-atmosphere interactions and validating simulation tools. There are several areas in which the data can be used for future research. The first is further benchmarking studies focused on AWAKEN's seven testable hypotheses. This includes assessing the accuracy and quantifying the uncertainty of various numerical models, ranging from engineering models like Flow Redirection and Induction in Steady State (FLORIS) to high-fidelity, large-eddy simulation codes like AMR-Wind and Nalu-Wind, as well as multiscale models like Weather Research and Forecasting (WRF). As part of these benchmarks we hope to investigate more in-depth sources of model uncertainty and error, particularly when using different simulation methods.

Next, we hope to improve wake models, especially those that include farm-scale physics. This could involve developing farm -level engineering wake models that account for relevant physics like blockage, local speedup, aggregate wake merging, and farm boundary-layer formation to help optimize farm performance at a regional scale. There is also room for improvement in Reynolds-averaged Navier-Stokes (RANS) wake models, particularly regarding farm-to-farm interactions. Coupling RANS and machine learning models could also advance capabilities for complex and variable inflow conditions.

AWAKEN data will also be useful for quantifying blockage and speedup effects. A detailed characterization of induction zone and speedup regions under different operative and atmospheric conditions through real-scale field experiments is still lacking. Future studies using this data could focus on validating the magnitude of deceleration and spatial extent of the induction zone, while differentiating between blockage and terrain effects.

Future analysis of the AWAKEN data can also include characterizing different types of gravity wave and atmospheric bore events observed during AWAKEN to better understand their formation mechanisms and effects on wind farm power production. Developing a methodology to classify gravity waves and assess their power production impacts is an identified area of future research.

Further research on lidar scanning strategies is needed to generalize tilted profiling models for different flows and estimate errors. Exploring completely novel scanning patterns specifically designed for tilted profiling is also suggested. Addressing the bias in second-order statistics obtained from tilted scans is also an area for further investigation.

Lastly, conducting additional campaign-wide analysis of data sets from AWAKEN sites and a detailed assessment of mesoscale and synoptic-scale conditions are next steps to help determine the physical basis for observed phenomena like vertical mixing and updrafts. Examining seasonal and case-by-case variability using the AWAKEN data set can help understanding of whether these findings can be generalized to other locations and time periods.

5.0 Public Outreach

The public outreach strategy was multi-pronged with a primary goal of reaching a large audience of atmospheric scientists and wind energy researchers to make the community aware of the data and ensure their widespread usage. Outreach also included presentations at conferences attended by industry members and meetings for the general public. AWAKEN was also publicized through multiple web pages, news stories, and a public data repository for continued data access.

The primary webpage for the project is https://www.nrel.gov/wind/awaken (National Renewable Energy Laboratory 2025), and data from the campaign are available at the DOE Wind Data Hub at https://doi.org/10.21947/AWAKEN/1914202 (U.S. Department of Energy 2025). Two notable articles were released by the ARM User Facility (Finnell-Gudwien 2023) and NOAA (NOAA Chemical Sciences Laboratory 2023).

In addition to the numerous publications and presentations given at conferences (listed in the next section), the AWAKEN project has held monthly public webinars that discuss the latest analysis and scientific findings resulting from the detailed AWAKEN observations. Webinars had a combined audience of approximately 60 researchers and industry participants.

Lastly, in September 2023, AWAKEN project partners hosted a two-day community event open to the public. The event, attended by many local landowners, featured science presentations by researchers and a tour of several instrument sites to educate a broader audience on the science being performed.

6.0 AWAKEN Publications

6.1 Journal Articles/Manuscripts

Abraham, A, N Hamilton, N Bodini, B Hirth, J Schroeder, S Letizia, R Krishnamurthy, R Newsom, and P Moriarty. 2024. “Land-based wind plant wake characterization using dual-Doppler radar measurements at AWAKEN.” *Journal of Physics: Conference Series* 2767(9): 092037, https://doi.org/10.1088/1742-6596/2767/9/092037

Ahmed, WU, C Moss, S Roy, M Shams Solari, M Puccioni, K Panthi, P Moriarty, and GV Iungo. 2024. “Wind farm wakes and farm-to-farm interactions: Lidar and wind tunnel tests.” *Journal of Physics: Conference Series* 2767(9): 092105, https://doi.org/10.1088/1742-6596/2767/9/092105

Bodini, N, A Abraham, P Doubrawa, S Letizia, R Thedin, N Agarwal, B Carmo, L Cheung, WC Radünz, A Gupta, L Goldberger, N Hamilton, T Herges, B Hirth, GV Iungo, A Jordan, C Kaul, P Klein, R Krishnamurthy, JK Lundquist, E Maric, P Moriarty, C Moss, R Newsom, Y Pichugina, M Puccioni, E Quon, S Roy, D Rosencrans, M Sanchez Gomez, R Scott, M Shams Solari, TJ Taylor, and S Wharton. 2024. “An international benchmark for wind plant wakes from the American WAKE ExperimeNt (AWAKEN).” *Journal of Physics: Conference Series* 2767(9): 092034, https://10.1088/1742-6596/2767/9/092034

Bodini, N, P Doubrawa, N Hamilton, T Herges, C Kaul, R Krishnamurthy, S Letizia, P Moriarty, J Naughton, A Scholbrock, and A Shamus. 2024. Lessons learned from the planning of recent Wind Energy Technologies Office field campaigns. NREL/TP-5000-90202. National Renewable Energy Laboratory, Golden, Colorado.

Bodini, N, JK Lundquist, H Livingston, and P Moriarty. 2022. "How generalizable is a machine-learning approach for modeling hub-height turbulence intensity?" *Journal of Physics: Conference Series* 2265(2): 022028, https://doi.org/10.1088/1742-6596/2265/2/022028

Bodini, N, JK Lundquist, and P Moriarty. 2021. "Wind plants can impact long-term local atmospheric conditions." *Scientific reports* 11(1): 22939, https://doi.org/10.1038/s41598-021-02089-2

Brown, K, L Cheung, N Develder, T Herges, A Hsieh, M Blaylock, G Yalla, R Knaus, D Maniaci, and B Hirth. 2024. "Estimating uncertainties from dual-Doppler radar measurements of onshore wind plants using les." *Journal of Physics: Conference Series* 2767(9): 092111, https://doi.org/10.1088/1742-6596/2767/9/092111

Cheung, L, A Hsieh, M Blaylock, T Herges, N Develder, K Brown, P Sakievich, D Houck, D Maniaci, C Kaul, R Rai, N Hamilton, A Rybchuk, R Scott, R Thedin, M Brazell, M Churchfield, and M Sprague. 2023. "Investigations of farm-to-farm interactions and blockage effects from AWAKEN using large-scale numerical simulations." *Journal of Physics: Conference Series* 2505(1): 012023, https://doi.org/10.1088/1742-6596/2505/1/012023

Cheung, L, ASK Hsieh, ML Blaylock, T Herges, N deVelder, K Brown, P Sakievich, DR Houck, DC Maniaci, C Kaul, et al. 2023. AWAKEN wind plant simulation comparison. Sandia National Laboratory, Livermore, California.

Cheung, L, G Yalla, K Brown, N deVelder, A Hsieh, T Herges, D Houck, D Maniaci, P Sakievich, and A Abraham. 2024. "Modification of wind turbine wakes by large-scale, convective atmospheric boundary layer structures." *Journal of Renewable and Sustainable Energy* 16(6): 063304, https://doi.org/10.1063/5.0211722

Debnath, M, P Moriarty, R Krishnamurthy, N Bodini, R Newsom, E Quon, JK Lundquist, S Letizia, GV Iungo, and P Klein. 2023. "Characterization of wind speed and directional shear at the AWAKEN field campaign site." *Journal of Renewable and Sustainable Energy* 15(3): 033308, https://doi.org/10.1063/5.0139737

Debnath, M, AK Scholbrock, D Zalkind, P Moriarty, E Simley, N Hamilton, C Ivanov, RS Arthur, R Barthelmie, N Bodini, A Brewer, L Goldberger, T Herges, B Hirth, GV Iungo, D Jager, C Kaul, P Klein, R Krishnamurthy, S Letizia, JK Lundquist, D Maniaci, R Newsom, M Pekour, SC Pryor, MT Titsche, J Roadman, J Schroeder, WJ Shaw, J van Dam, and S Wharton. 2022. "Design of the American Wake Experiment (AWAKEN) field campaign." *Journal of Physics: Conference Series* 2265(2): 022058, https://doi.org/10.1088/1742-6596/2265/2/022058

Finnell-Gudwien, G. (2023, July). AWAKEN: Improving Wind Farms [Accessed: 2025-05-29]. Atmospheric Radiation Measurement (ARM) User Facility. https://www.arm.gov/news/features/post/89421

Hirth, B, J Schroeder, and J Guynes. 2024. "An onshore deployment of advanced dual-Doppler radar for wind energy applications." *Journal of Physics: Conference Series* 2745(1): 012013, https://doi.org/10.1088/1742-6596/2745/1/012013

Hsieh, AS, LC Cheung, ML Blaylock, KA Brown, DR Houck, TG Herges, NB Develder, DC Maniaci, GR Yalla, PJ Sakievich, WC Radünz, and BS Carmo. 2025. "Model intercomparison of the ABL, turbines, and wakes within the AWAKEN wind farms under neutral stability conditions." *Journal of Renewable and Sustainable Energy* 17(2): 023301, https://doi.org/10.1063/5.0211729

Hung, L-Y, J Gottschall, AL Vohringer, BD Hirth, and J Schroeder. 2024. "Comparison of line-of-sight wind speed measurements from an x-band radar and a long-range scanning lidar." *Journal of Physics: Conference Series* 2767(4): 042030, https://doi.org/10.1088/1742-6596/2767/4/042030

Iungo, GV, R Maulik, SA Renganathan, and S Letizia. 2022. "Machine-learning identification of the variability of mean velocity and turbulence intensity for wakes generated by onshore wind turbines: Cluster analysis of wind LiDAR measurements." *Journal of Renewable and Sustainable Energy* 14(2): 023307, https://doi.org/10.1063/5.0070094

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 (AWAKEN) campaign." *Journal of Renewable and Sustainable Energy* 16(6): 063305, https://doi.org/10.1063/5.0211717

Krishnamurthy, R, RK Newsom, CM Kaul, S Letizia, M Pekour, N Hamilton, D Chand, D Flynn, N Bodini, and P Moriarty. 2025. "Observations of wind farm wake recovery at an operating wind farm." *Wind Energy Science* 10(2): 361–380, https://doi.org/ 10.5194/wes-10-361-2025

Letizia, S, N Bodini, P Brugger, A Scholbrock, N Hamilton, F Porté-Agel, P Doubrawa, and P Moriarty. 2023. "Holistic scan optimization of nacelle-mounted lidars for inflow and wake characterization at the RAAWand AWAKEN field campaigns." *Journal of Physics: Conference Series* 2505(1): 012048, https://doi.org/10.1088/1742-6596/2505/1/012048

Letizia, S, R Robey, N Bodini, M Sanchez Gomez, JK Lundquist, R Krishnamurthy, and PJ Moriarty. 2024. "Tilted lidar profiling: Development and testing of a novel scanning strategy for inhomogeneous flows." *Journal of Renewable and Sustainable Energy* 16(4): 043310, https://doi.org/10.1063/5.0209729

Michaud-Belleau, V, M Gaudreau, J Lacoursière, É Boisvert, L Ravelomanantsoa, DD Turner, and L Rochette. 2025. "The Atmospheric Sounder Spectrometer by Infrared Spectral Technology (ASSIST): Instrument design and signal processing." *Atmospheric Measurement Techniques Discussions* 20: 1–39, https://doi.org/10.5194/egusphere-2024-3617

Miller, LM, and DW Keith. 2018. "Climatic impacts of wind power." *Joule* 2(12): 2618–2632, https://doi.org/10.1016/j.joule.2018.09.009

Mlawer, EJ, and DD Turner. 2016. "Spectral radiation measurements and analysis in the ARM program." *Meteorological Monographs* 57: 14.1–14.17, https://doi.org/10.1175/amsmonographs-d-15-0027.1

Moriarty, P, N Bodini, L Cheung, N Hamilton, T Herges, C Kaul, S Letizia, M Pekour, and E Simley. 2023. "Overview of recent observations and simulations from the American WAKE experimeNt (AWAKEN) field campaign." *Journal of Physics: Conference Series* 2505(1): 012049, https://doi.org/10.1088/1742-6596/2505/1/012049

Moriarty, P, N Bodini, S Letizia, A Abraham, T Ashley, KB Bärfuss, RJ Barthelmie, A Brewer, P Brugger, T Feuerle, A Frère, L Goldberger, J Gottschall, N Hamilton, T Herges, B Hirth, L-Y Hung, G Valerio Iungo, H Ivanov, C Kaul, S Kern, P Klein, R Krishnamurthy, A Lampert, JK Lundquist, VR Morris, R Newsom, M Pekour, Y Pichugina, F Porté-Angel, SC Pryor, A Scholbrock, J Schroeder, S Shartzer, E Simley, L Vöhringer, S Wharton, and D Zalkind. 2024. "Overview of preparation for the American WAKE ExperimeNt (AWAKEN)." *Journal of Renewable and Sustainable Energy* 16(5): 053306, https://doi.org/10.1063/5.0141683

Moriarty, P, N Hamilton, M Debnath, T Herges, B Isom, JK Lundquist, D Maniaci, B Naughton, R Pauly, J Roadman, W Shaw, J van Dam, and S Wharton. 2020. American WAKE experiment (AWAKEN). Lawrence Livermore National Laboratory, National Renewable Energy Laboratory, Sandia National Laboratory, Pacific Northwest National Laboratory, University of Colorado. https://www.osti.gov/biblio/1806419

Moss, C, R Maulik, P Moriarty, and GV Iungo. 2024. "Predicting wind farm operations with machine learning and the P2D-RANS model: A case study for an AWAKEN site." *Wind Energy* 27(11): 1245–1267, https://doi.org/10.1002/we.2874

Nadolsky, J, J Schroeder, and B Hirth. 2024. "Extracting atmospheric stability information from dual-Doppler radar scans in the AWAKEN campaign." *Journal of Physics: Conference Series* 2767(4): 042012, https://doi.org/10.1088/1742-6596/2767/4/042012

National Renewable Energy Laboratory. 2025. AWAKEN: The American WAKE experiment [Accessed: 2025-05-29], https://www.nrel.gov/wind/awaken

Newsom, R, R Krishnamurthy, D Chand, M Pekour, C Kaul, D Flynn, L Goldberger, R Rai, and S Wharton. 2024. "Virtual tower measurements during the American WAKE ExperimeNt (AWAKEN)." *Journal of Renewable and Sustainable Energy* 16(4): 046501, https://doi.org/10.1063/5.0206844

Newsom, R, R Krishnamurthy, C Kaul, D Chand, and M Pekour. 2024. AWAKEN Dual-Doppler Lidar (ADDLidar) Field Campaign Report. DOE/SC-ARM-24-035. U.S. Department of Energy, Atmospheric Radiation Measurement User Facility, Richland, Washington.

NOAA Chemical Sciences Laboratory. 2023. AmericanWAKE experimeNt (AWAKEN) [Accessed: 2025-05-29]. https://csl.noaa.gov/groups/csl3/measurements/2023awaken/

Pronk, V, N Bodini, M Optis, JK Lundquist, P Moriarty, C Draxl, A Purkayastha, and E Young. 2022. "Can reanalysis products outperform mesoscale numerical weather prediction models in modeling the wind resource in simple terrain?" *Wind Energy Science* 7(2): 487–504, https://doi.org/10.5194/wes-7-487-2022

Puccioni, M, C Moss, C Jacquet, and G Iungo. 2023. "Blockage and speedup in the proximity of an onshore wind farm: A scanning wind LiDAR experiment." *Journal of Renewable and Sustainable Energy* 15(5): 053307, https://doi.org/10.1063/5.0157937

Puccioni, M, C Moss, M Solari, S Roy, G Iungo, S Wharton, and P Moriarty. 2024. "Quantification and assessment of the atmospheric boundary layer height measured during the AWAKEN experiment by a scanning LiDAR." *Journal of Renewable and Sustainable Energy* 16(5): 053304, https://doi.org/10.1063/5.0211259

Puccioni, M, GV Iungo, C Moss, MS Solari, S Letizia, N Bodini, and P Moriarty. 2023. "LiDAR measurements to investigate farm-to-farm interactions at the AWAKEN experiment." *Journal of Physics: Conference Series* 2505(1): 012045, https://doi.org/10.1099/1742-6596/2505/1/012045

Radünz, W, B Carmo, B., JK Lundquist, S Letizia, A Abraham, AS Wise, M Sanchez Gomez, N Hamilton, RK Rai, and PS Peixoto. 2025. "Influence of simple terrain on the spatial variability of a low-level jet and wind farm performance in the awaken field campaign." *Wind Energy Science Discussions* 2025: 1–38, https://doi.org/10.5194/wes-2024-166

Rajewski, DA, ES Takle, JK Lundquist, S Oncley, JH Prueger, TW Horst, ME Rhodes, R Pfeiffer, JL Hatfield, KK Spoth, and RK Doorenbos. 2013. "CropWind Energy Experiment (CWEX): Observations of surface-layer, boundary layer, and mesoscale interactions with a wind farm." *Bulletin of the American Meteorological Society* 94(5): 655–672, https://doi.org/10.1175/BAMS-D-11-00240.1

Sanchez Gomez, M, JK Lundquist, JD Mirocha, RS Arthur, D Muñoz-Esparza, and R Robey. 2022. "Can lidars assess wind plant blockage in simple terrain? a WRF-LES study." *Journal of Renewable and Sustainable Energy* 14(6): 063304, https://doi.org/10.1063/5.0103668

Scott, R, N Hamilton, RB Cal, and P Moriarty. 2024. "Wind plant wake losses: Disconnect between turbine actuation and control of plant wakes with engineering wake models." *Journal of Renewable and Sustainable Energy* 16(4): 043303, https://doi.org/10.1063/5.0207013

Simley, E, P Fleming, N Girard, L Alloin, E Godefroy, and T Duc. 2021. "Results from a wake-steering experiment at a commercial wind plant: Investigating the wind speed dependence of wake-steering performance." *Wind Energy Science* 6(6): 1427–1453, https://doi.org/10.5194/wes-6-1427-2021

Smith, CM, RJ Barthelmie, and SC Pryor. 2013. "In situ observations of the influence of a large onshore wind farm on near-surface temperature, turbulence intensity and wind speed profiles." *Environmental Research Letters* 8(3): 034006, https://doi.org/10.1088/1748-9326/8/3/034006

Turner, DD, and WG Blumberg. 2019. "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

U.S. Department of Energy. 2025. American WAKE experimeNt (AWAKEN). [Accessed: 2025-05-29]. https://doi.org/10.21947/AWAKEN/1914202

Wise, AS, RS Arthur, A Abraham, S Wharton, R Krishnamurthy, R Newsom, B Hirth, J Schroeder, P Moriarty, and FK Chow. 2024. "Large-eddy simulation of an atmospheric bore and associated gravity wave effects on wind farm performance in the Southern Great Plains." *Wind Energy Science Discussions* 2024: 1–35, https://doi.org/10.5194/wes-10-1007-2025

Wu, S, and CL Archer. 2021. "Near-ground effects of wind turbines: Observations and physical mechanisms." *Monthly Weather Review* 149(3): 879–898, https://doi.org/10.1175/ MWR-D-20-0186.1

Wu, S, CL Archer, and JD Mirocha. 2023. "New insights on wind turbine wakes from large-eddy simulation: Wake contraction, dual nature, and temperature effects." *Wind Energy* 27(11): 1130–1151, https://doi.org/10.1002/we.2827

Xia, G, L Zhou, JR Minder, RG Fovell, and PA Jimenez. 2019. "Simulating impacts of real-world wind farms on land surface temperature using the WRF model: Physical mechanisms." *Climate Dynamics* 53(3-4): 1723–1739, https://doi.org/10.1007/s00382-019-04725-0

Zhou, L, Y Tian, S Baidya Roy, C Thorncroft, LF Bosart, and Y Hu. 2012. "Impacts of wind farms on land surface temperature." *Nature Climate Change* 2(7): 539–543, https://doi.org/10.1038/nclimate1505

6.2 Meeting Abstracts/Presentations/Posters

Conference	Lead Author	Presentation Title
TORQUE 2022	Debnath M.	Design of the American Wake Experiment (AWAKEN) field campaign
	Bodini N.	How generalizable is a machine learning approach for modeling hub-height turbulence intensity?
NAWEA 2022	Moss C.	Predicting wind farm operations with machine learning and the P2D-RANS model: A case study for an AWAKEN site
AMS 2023	Moriarty P.	Overview of the American Wake Experiment (AWAKEN)
WESC 2023	Hirth B.	Dual-Doppler radar measurements of wind farm wakes and interaction during project AWAKEN
	Lundquist J.	Can lidars assess wind plant blockage in the simple terrain of the AWAKEN domain? A WRF-LES study
	Hamilton N.	Wind turbine control for mutual benefit in multi-plant systems
	Brown K.	Preliminary analysis of farm-wide lidar and radar results in the AWAKEN experiment
	Moriarty P.	The American WAKE experimeNt: an overview
	Letizia S.	Thermodynamic properties of the atmospheric boundary layer profiles retrieved through ground-based infrared spectral radiometers for AWAKEN
	Simley E.	Overview and design of the wind farm control system for the American Wake Experiment (AWAKEN)
	Wise A.	Multi-scale modeling of intermittent turbulence effects on wind farm performance in the U.S. Great Plains
	Nadolsky J.	4D wind evaluations of turbine inflow and wake flow using research radar measurements
	Hung L.	Scanning lidar and X-band radar verification @AWAKEN

Conference	Lead Author	Presentation Title
ARM/ASR 2023	Moriarty P.	Observations of wind farm atmosphere interactions within the American Wake Experiment (AWAKEN)
	Newsom R.	Virtual tower measurements during AWAKEN
NAWEA 2023	Letizia S.	Retrieval of the thermodynamic properties of the ABL at the AWAKEN site
	Krishnamurthy R.	Observations of momentum flux profiles around a wind farm
	Puccioni M.	Estimating the atmospheric boundary-layer height based on LiDAR and single-point measurements
	Hirth B.	Dual-Doppler radar documentation of wind farm interaction and regional wind flows during project AWAKEN
	Cheung L.	Development of analytical blockage models capturing shear and atmospheric stratification
	Hsieh A.	An investigation of wake turbulence and turbine loading for the AWAKEN wind farms
Wake Conference 2023	Puccioni M.	LiDAR measurements to investigate farm-to-farm interactions at the AWAKEN experiment
	Letizia S.	Holistic scan optimization of nacelle-mounted lidars for inflow and wake characterization at the RAAW and AWAKEN field campaigns
	Cheung L.	Investigations of farm-to-farm interactions and block-age effects from AWAKEN using large-scale numerical simulations
	Moriarty P.	Overview of recent observations and simulations from the American WAKE experimeNt (AWAKEN) field campaign
APS DFD 2023	Abraham A.	Investigation of wind plant wake effects at the AWAKEN field campaign
AMS 2024	Abraham A.	Wind plant impacts on planetary boundary-layer height
	Bodini N.	The American Wake Experiment (AWAKEN): leveraging observations to create international benchmarks
Torque 2024	Abraham A.	Land-based wind plant wake characterization using dual-Doppler radar measurements at AWAKEN
	Ahmed W.	Wind farm wakes and farm-to-farm interactions: Lidar and wind tunnel tests
	Bodini N.	Leveraging observations from the American Wake Experiment (AWAKEN) to create international benchmarks on wind plant wakes
	Vöhringer L.	Comparison of horizontal wind speed and direction measurements from dual-Doppler radar and profiling lidar
	Brown K.	Estimating uncertainties from dual-Doppler radar measurements of onshore wind plants using LES
	Nadolsky J.	Extracting atmospheric stability information from dual-Doppler radar scans in the AWAKEN campaign
	Hung L.	Comparison of line-of-sight wind speed measurements from Doppler radar and a long-range scanning lidar — a verification methodology and uncertainty assessment

Conference	Lead Author	Presentation Title
Wind Europe 2024	Hirth B.	An onshore deployment of advanced dual-Doppler radar for wind energy applications
31st International Laser Radar Conference	Pichugina Y.	Emerging mobile micropulsed-Doppler lidar technology for wind energy research
NAWEA 2024	Bodini N.	An international benchmark on wind plant wakes from the American Wake Experiment (AWAKEN)
	Letizia S.	Tilted lidar profiling: development and testing of a novel scanning strategy for inhomogeneous flows
	Radünz W.	Determining optimal initial/boundary conditions for AWAKEN mesoscale wake benchmark
	Abraham A.	Wind plant impacts on planetary boundary-layer height at the AWAKEN field site
	Hsieh A.	Field data validation of neutral AWAKEN simulations using various models
	Goldberger L.	AWAKEN campaign observations of precipitation from hub height, inflow, and outflow regions of the King Plains wind farm
	Wise A.	How do an atmospheric bore and associated gravity waves affect wind farm performance?
	Lundquist J.	Impact of wind plants on nocturnal temperatures within and downwind of wind plants as seen in AWAKEN observations and simulations
	Nadolsky J.	Characterizing turbine inflows and interactions via radar-derived and SCADA-retrieved wind measurements
	Houck D.	Validation of the open-source GE2.8-127 OpenFAST turbine
	Ramm E.	Wind turbines in Oklahoma attract lightning
	Brown K.	Farm-scale validation of LES wake predictions lever-aging onshore, dual-Doppler radar
ACP RT 2024	Bodini N.	An international benchmark on wind plant wakes from the American Wake Experiment (AWAKEN)
AGU 2024	Abraham A.	Wind plant impacts on planetary boundary-layer height at the AWAKEN field site
	Barthelmie R.	Wake characterization during AWAKEN
	Lundquist J.	Impact of wind plants on nocturnal temperatures within and downwind of wind plants as seen in AWAKEN observations and simulations
	Radünz W.	How the spatial variability of winds affects mesoscale wind farm wakes over the diurnal cycle at the AWAKEN site

Conference	Lead Author	Presentation Title
	Voss A.	Investigation of the interaction of onshore wind farm wakes with the atmospheric boundary layer during AWAKEN with in situ aircraft measurements
	Wise A.	Stable boundary- layer turbulence implications for wind energy: Insights from the AWAKEN field campaign
AMS 2025	Pichugina Y.	Spatio-temporal variability of boundary-layer winds within wind farms from truck-based mobile lidar measurements
AMS BLT 2025	Lundquist J.	Evaluation of wind farm wake modeling using AWAKEN ground-based and airborne measurements
WESC 2025	Moriarty P.	The American Wake Experiment (AWAKEN): past, present, and future
	Bodini N.	Results from the AWAKEN international wind farm wake benchmark
	Simley E.	Assessment of consensus and wake steering wind farm control for AWAKEN
	Letizia S.	Thermodynamic profiling around wind plants: uncertainty quantification and evidence of thermal wakes
	Lundquist J.	Evaluation of wind farm wake modeling using AWAKEN ground-based and airborne measurements
	Hamilton N.	A modal description of dynamic wake meandering Abraham characterization of extreme wind ramps at AWAKEN
	Nadolsky J.	Investigating differences in remotely sensed wind speed measurements from the AWAKEN campaign
	Hirth B.	An overview of the versatility of specialized Doppler radar to inform wind energy applications

7.0 References

Abraham, A, N Hamilton, N Bodini, B Hirth, J Schroeder, S Letizia, R Krishnamurthy, R Newsom, and P Moriarty. 2024. "Land-based wind plant wake characterization using dual-Doppler radar measurements at AWAKEN." *Journal of Physics: Conference Series* 2767(9): 092037, https://doi.org/10.1088/1742-6596/2767/9/092037

Bodini, N, A Abraham, P Doubrawa, S Letizia, R Thedin, N Agarwal, B Carmo, L Cheung, WC Radünz, A Gupta, L Goldberger, N Hamilton, T Herges, B Hirth, GV Iungo, A Jordan, C Kaul, P Klein, R Krishnamurthy, JK Lundquist, E Maric, P Moriarty, C Moss, R Newsom, Y Pichugina, M Puccioni, E Quon, S Roy, D Rosencrans, M Sanchez Gomez, R Scott, M Shams Solari, TJ Taylor, and S Wharton. 2024. "An international benchmark for wind plant wakes from the American WAKE ExperimeNt (AWAKEN)." *Journal of Physics: Conference Series* 2767(9): 092034, https://doi.org/10.1088/1742-6596/2767/9/092034

Bodini, N, P Doubrawa, N Hamilton, T Herges, C Kaul, R Krishnamurthy, S Letizia, P Moriarty, J Naughton, A Scholbrock, and A Shamus. 2024. Lessons learned from the planning of recent Wind Energy Technologies Office field campaigns. NREL/TP-5000-90202. National Renewable Energy Laboratory, Golden, Colorado.

Finnell-Gudwien, G. 2023. AWAKEN: Improving Wind Farms [Accessed: 2025-05-29]. Atmospheric Radiation Measurement (ARM) User Facility. https://www.arm.gov/news/features/post/89421

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 (AWAKEN) campaign." *Journal of Renewable and Sustainable Energy* 16(6): 063305, https://doi.org/10.1063/5.0211717

Krishnamurthy, R, RK Newsom, CM Kaul, S Letizia, M Pekour, N Hamilton, D Chand, D Flynn, N Bodini, and P Moriarty. 2025. "Observations of wind farm wake recovery at an operating wind farm." *Wind Energy Science* 10(2): 361–380, https://doi.org/10.5194/wes-10-361-2025

Michaud-Belleau, V, M Gaudreau, J Lacoursière, É Boisvert, L Ravelomanantsoa, DD Turner, and L Rochette. 2025. "The Atmospheric Sounder Spectrometer by Infrared Spectral Technology (ASSIST): Instrument design and signal processing." *Atmospheric Measurement Techniques Discussions* 20(February), 1–39, https://doi.org/10.5194/egusphere-2024-3617

Miller, LM, and DW Keith. 2018. "Climatic impacts of wind power." *Joule* 2(12): 2618–2632, https://doi.org/10.1016/j.joule.2018.09.009

Mlawer, EJ, and DD Turner. 2016. "Spectral radiation measurements and analysis in the ARM program." *Meteorological Monographs* 57: 14.1–14.17, https://doi.org/10.1175/amsmonographsd-15-0027.1

Moriarty, P, N Bodini, S Letizia, A Abraham, T Ashley, KB Bärfuss, RJ Barthelmie, A Brewer, P Brugger, T Feuerle, A Frère, L Goldberger, J Gottschall, N Hamilton, T Herges, B Hirth, L-Y Hung, GV Iungo, H Ivanov, C Kaul, S Kern, P Klein, R Krishnamurthy, A Lampert, JK Lundquist, VR Morris, R Newxom, M Pekour, Y Pichugina, F Porté-Angel, SC Pryor, A Scholbrock, J Schroeder, S Shartzer, E Simley, L Vöhringer, S Wharton, and D Zalkind. 2024. "Overview of preparation for the American WAKE ExperimeNt (AWAKEN)." *Journal of Renewable and Sustainable Energy* 16(5): 053306, https://doi.org/10.1063/5.0141683

Moriarty, P, N Hamilton, M Debnath, T Herges, B Isom, JK Lundquist, D Maniaci, B Naughton, R Pauly, J Roadman, W Shaw, J van Dam, and S Wharton. 2020. American WAKE experiment (AWAKEN). Lawrence Livermore National Laboratory, National Renewable Energy Laboratory, Sandia National Laboratories, Pacific Northwest National Laboratory, University of Colorado. https://www.osti.gov/biblio/1806419

National Renewable Energy Laboratory. 2025. AWAKEN: The American WAKE experiment [Accessed: 2025-05-29]. https://www.nrel.gov/wind/awaken

Newsom, R, R Krishnamurthy, D Chand, M Pekour, C Kaul, D Flynn, L Goldberger, R Rai, and S Wharton. 2024. "Virtual tower measurements during the American WAKE ExperimeNt (AWAKEN)." *Journal of Renewable and Sustainable Energy* 16(4): 046501, https://doi.org/10.1063/5.0206844

Newsom, R, R Krishnamurthy, C Kaul, D Chand, and M Pekour. 2024. AWAKEN Dual-Doppler Lidar (ADDLidar) field campaign Report. DOE/SC-ARM-24-035. U.S. Department of Energy, Atmospheric Radiation Measurement User Facility, Richland, Washington.

NOAA Chemical Sciences Laboratory. 2023. American WAKE experimeNt (AWAKEN) [Accessed: 2025-05-29]. https://csl.noaa.gov/groups/csl3/measurements/2023awaken/

Radünz, W, B Carmo, JK Lundquist, S Letizia, A Abraham, AS Wise, M Sanchez Gomez, N Hamilton, RK Rai, and PS Peixoto. 2025. "Influence of simple terrain on the spatial variability of a low-level jet and wind farm performance in the awaken field campaign." *Wind Energy Science Discussions* 2025: 1–38, https://doi.org/10.5194/wes-2024-166

Rajewski, DA, ES Takle, JK Lundquist, S Oncley, JH Prueger, TW Horst, ME Rhodes, R Pfeiffer, JL Hatfield, KK Spoth, and RK Doorenbos. 2013. "CropWind Energy Experiment (CWEX): Observations of surface-layer, boundary layer, and mesoscale interactions with a wind farm." *Bulletin of the American Meteorological Society* 94(5): 655–672, https://doi.org/10.1175/BAMS-D-11-00240.1

Smith, CM, RJ Barthelmie, and SC Pryor. 2013. "In situ observations of the influence of a large onshore wind farm on near-surface temperature, turbulence intensity and wind speed profiles." *Environmental Research Letters* 8(3): 034006, https://doi.org/10.1088/1748-9326/8/3/034006

Turner, DD, and WG Blumberg. 2019. "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

U.S. Department of Energy. 2025. American WAKE experimeNt (AWAKEN) [Accessed: 2025-05-29]. https://doi.org/10.21947/AWAKEN/1914202

Wu, S, and CL Archer. 2021. "Near-ground effects of wind turbines: Observations and physical mechanisms." *Monthly Weather Review* 149(3): 879–898, https://doi.org/10.1175/MWRD-20-0186.1

Wu, S, CL Archer, and JD Mirocha. 2023. "New insights on wind turbine wakes from large-eddy simulation: Wake contraction, dual nature, and temperature effects." *Wind Energy* 27(11): 1130–1151, https://doi.org/10.1002/we.2827

Xia, G, L Zhou, JR Minder, RG Fovell, and PA Jimenez. 2019. "Simulating impacts of real-world wind farms on land surface temperature using the WRF model: Physical mechanisms." *Climate Dynamics* 53(3–4): 1723–1739, https://doi.org/10.1007/s00382-019-04725-0

Zhou, L, Y Tian, S Baidya Roy, C Thorncroft, LF Bosart, and Y Hu. 2012. "Impacts of wind farms on land surface temperature". *Nature Climate Change* 2(7): 539–543, https://doi.org/10.1038/nclimate1505

8.0 Lesson Learned

A lessons learned document focused on recent wind energy field campaigns, including AWAKEN, was published as a National Renewable Energy Laboratory technical report (Bodini et al. 2024).

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