ATOC 5770 Literature Review
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This project will analyze data from the American WAKE experiment (AWAKEN) field campaign in Oklahoma. The objective is to answer the following question:

- What is the frequency of low-level jets (LLJs) in the area where C1a and A2 lidars operated?

This document surveys some of the related literature to inform, contextualize, and motivate the proposed project.

While wind farm technology has seen rapid growth and improvement, there still exist several problems to overcome over several scales of space and time. Improved understanding of the physics of atmospheric flow and interaction with wind turbines has been identified as a grand challenge in wind energy research (Veers et al., 2019). Improved understanding of atmospheric flows will inform techniques to maximize the efficiency and therefore cost effectiveness of wind plants.

Diurnal low-level jets (LLJs) are an impactful weather event found around the world, driving the transportation of moisture, pollutants, dust, and other airborne substances for thousands of kilometers, all within the atmospheric boundary layer (Rife et al., 2010). These phenomena also impact wind farms, as modern turbines reach heights where LLJs commonly occur. LLJs can increase power output but can also cause damage to wind turbines. The Great Plains region of the United States experiences strong nocturnal LLJs during the warm season, which can be hundreds of kilometers wide and thousands of kilometers long. As this region is also home to much of our wind power resources, understanding LLJs is of great importance.

One of the first studies of LLJs in the U.S. Great Plains was conducted and presented in (Bonner, 1968). The author used two years of radiosonde data from 46 weather stations to identify hundreds of cases of nocturnal LLJs using a criterion developed therein. The diurnal variation and oscillation of the LLJ was observed throughout the year, although most often in spring and late summer. This landmark study provided substantial proof of the prominence and massive scales of LLJs in the region which significantly impact the local climate.

A more recent climatology of LLJs in the Great Plains of the United States provided more detail on general trends in the region (Walters et al., 2008). This study combined forty years of twice-daily radiosonde observations from 36 weather stations across the Great Plains. The authors were able to identify several characteristics of LLJs which vary based on seasonality and location. While this paper helped provide a broad description of LLJs in the region, the authors conclude that much remains to be documented and understood.

The AWAKEN program is a landmark international campaign to collect measurements of wake interactions within wind power plants, spearheaded by the National Renewable Energy Lab (Moriarty et al., 2020). The motivation for this campaign is the poorly understood effect that wake interactions have within wind plants, which leads to significant and unpredictable power and financial losses. High-fidelity, long duration data will be gathered in north-central Oklahoma, an area important and relevant for near-term wind energy developments in the U.S. Great Plains. This data is critical for the development and validation of models which will in turn inform wind development projects and ultimately reduce the cost of wind energy. Data will be collected from a variety of platforms, though this project will leverage lidar measurements of the ABL, data which can be used to study local occurrences of LLJs and Kelvin-Helmholtz instability.

Other works have studied LLJs in the U.S. Great Plains using lidar measurements. In 2013, researchers deployed profiling and scanning lidars to collect data which was used to detect LLJs in central Iowa as part of the CWEX-13 field campaign (Vanderwende et al., 2015). The authors detailed a systematic procedure for computing wind profiles from the scanning lidar and using these profiles to detect and classify LLJs. LLJs were consistently identified, with peak windspeeds around 250-500m at the observation site, heights relevant to modern wind turbines. The authors also investigated the ability of various numerical weather models (and ensembles of said models) to predict LLJs in the area, demonstrating good performance. The LLJ classification procedure will be used in the proposed project to detect LLJs during the AWAKEN experiment.

Data from the CWEX-13 campaign was also used to characterize and study wake interactions from multiple turbines (Bodini et al., 2017). Again, a systematic procedure for identifying wakes from lidar measurements was presented. The researchers investigated both geometric and gaussian mixture models for the horizontal wind profile (downwind, perpendicular to the row of turbines). It was shown (for the first time, experimentally) that wind veer directly effects wakes by stretching them, resulting in angular changes in wake centerlines as a function of height. This phenomenon was observed to be greater for outer turbines.

Lidar data can also be paired with in situ tower sensors and radiosondes to rigorously measure and characterize turbulence in the ABL. This sensor combination for ABL sensing was demonstrated in the CASES-99 campaign in southeast Kansas (Blumen et al., 2001). This is important as LLJs can create sufficient mechanical forcing to induce turbulence and subsequent Kelvin-Helmholtz instability (KHI) billows. Richardson numbers of 0.13 were observed in the atmospheric layer that experienced KHI, which aligned with theory. These observations were essential in validating KHI and turbulence simulations.

Several other works and analyses on LLJs and shear-flow instability spurred from the CASES-99 campaign in southeastern Kansas. Researchers investigated a shear-flow instability which occurred over 30 minutes below a LLJ maximum (Newsom & Banta, 2003). It was shown that the observed instability was caused by an increase in shear due to flow slowing below the LLJ, while the speed and height of the LLJ remained essentially constant. The authors state it is not clear what caused this reduction in windspeed bellowing th LLJ. The lowest Richardson number observed during this event was approximately 0.1, indicating a turbulent environment. The authors were able to rigorously characterize the KHI wave characteristics, including wavelength, phase speed, and amplitude.

CASES-99 data was also used to characterize individual LLJ occurrences and trends with respect to topography, time of night, and spatial distribution (Banta et al., 2002). The site of study frequently saw LLJs at or below 100m AGL, which would certainty impact modern wind turbines. LLJs were found and classified using a relatively simple procedure which was heavily informed by visual inspection. It was shown, for this site, that higher sites tended to have higher windspeeds, and that LLJs tend to not be terrain following (i.e., they tend to have near constant MSL altitude).

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