Characterizing turbine inflow during a stability transition using dual-Doppler radar measurements

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Abstract. Measurements from two specialized Doppler radars are used to construct a dual-Doppler synthesis of the boundary layer wind flow during an unstable-to-stable transition. Three rotor sweep concepts are inserted into the flow to evaluate turbine inflow variability across the rotor sweeps. One-second turbine inflow forecasts are constructed using an advanced advection correction technique at each rotor grid point allowing for detailed statistical analysis of shear, veer, and turbulence intensity across the three rotor sweeps.

1. Introduction
Proper characterization of wind turbine inflow is vital for understanding and improving wind turbine design and performance. It is well recognized that the stability of the lower atmosphere has a direct impact on the structure of the wind flow in the boundary layer¹,². As turbine rotors grow in size, so too can the horizontal and vertical variability of the wind impacting the full rotor sweep. In this study, three hypothetical rotor concepts (e.g. different hub heights and rotor diameters) are placed into a boundary layer characterized by a pronounced unstable-to-stable stability transition to examine the inflow evolution and variability that would exist across the rotor sweeps.

This study makes use of the measurements obtained by two mobile research radar systems in the United States Midwest to construct high spatial and temporal resolution dual-Doppler (DD) time histories of the evolving inflow into the three rotor concepts. The radars performed a series of sector scans at multiple elevation tilts; the measurements were used to construct three dimensional volumes of wind speed and direction information that span the depth of the rotor sweeps³. An advanced advection correction technique was then applied to the DD analysis volumes allowing for the extraction of second-by-second inflow time histories at multiple locations across each rotor sweep⁴. Using the one second inflow time histories, statistics were generated describing the shear, veer and turbulence intensity (TI) experienced across the three roto rs. The evolution of the inflow variability across the rotor sweep as a function of the stability regime was also examined. By making use of three different rotor concepts, relationships between rotor size and the aforementioned inflow variability can be investigated. These time histories and the subsequent statistics can contribute to an improved understanding of turbine loading conditions, while also advising on the potential to develop short-term forecasting methodologies⁵, and proactive control concepts. While this paper presents the results of a single case study which are likely to vary, these results introduce insights into the ways high fidelity radar-derived wind fields can be used to assess wind flow variability across the rotor sweep at turbulence scales.

2. Methodology
Texas Tech University owns, maintains and operates two mobile Ka-band (TTUKa) radars designed to measure engineering-relevant scales of wind flows in the lower atmosphere. The radars maintain a half-powered beamwidth of 0.33° and for this study used a pulse configuration yielding an along-beam range resolution of 15 m. The radars were deployed to
the United States Midwest to document the evolving wind structure during an afternoon to evening stability transition using established DD data collection techniques\textsuperscript{3,6,7}. The radar deployments were separated by 6.2 km and each radar scanned a 55° horizontal sector (Figure 1) at 30° s\textsuperscript{-1} for a series of 14 elevation tilts between 0.3° - 2.9° at 0.2° increments. The employed scanning strategy allowed for the construction of a single DD volume every 55 seconds. The scanned domain was characterized by relatively flat, open farm land containing primarily corn and wheat. The experiment was executed in late September in a non-precipitating environment. Crop harvesting was ongoing such that the land use was characterized by a mix of mature and harvested crops. For this study, a 2 km x 2 km horizontal subset of the full DD domain (the experimental domain) was extracted for a three-hour period to investigate small-scale wind variability relevant to wind energy applications. The prevailing wind direction was generally from the north-northeast throughout the experimental period.

![DD deployment schematic](image)

**Figure 1.** DD deployment schematic including background elevation (m). The location of TTUKa1 (blue square), TTUKa2 (red square), and their respective scanned sectors (blue and red lines, respectively) are shown. The 2 km x 2 km experimental domain is outlined in black. Wind direction for the experimental period was generally from the north-northeast.

Inserted into the experimental domain were three hypothetical rotor concepts (R1, R2, and R3) of various hub-height (HH0 and rotor diameter (D) sizes to investigate the associated rotor inflow variability (Table 1). The rotors were centered at x=500 m, y=500 m within the experimental domain. Data characterizing the inflows into these hypothetical rotors were interpolated to a 10 m grid resolution in the horizontal and vertical, and the resulting number of available data grid points increased substantially with increasing rotor size (Figure 2).

While individual DD volume revisit times were roughly 55 seconds, a space-to-time conversion process was used to extract higher resolution wind speed and direction time-history information at each grid point. Leveraging an advanced advection correction technique\textsuperscript{7}, second-by-second inflow forecasts were generated for all grid points contained within the three rotor sweeps. One facet of this technique is that it recognizes that gust and lull features do not necessarily propagate with the mean wind speed and/or direction at a given vertical height. Instead, the method uses a correlation technique to track dominant features in the wind flow from one volume to the next to establish the advection speed and direction. The resulting advection properties were then used to align the rotor sweeps towards the incoming wind...
Table 1. Details of the three hypothetical rotor concepts used for this summary.

| Rotor | HH (m) | D (m) | Number of Grid Points |
|-------|--------|-------|-----------------------|
| R1    | 80     | 80    | 49                    |
| R2    | 110    | 160   | 197                   |
| R3    | 150    | 200   | 377                   |

Figure 2. Top: Example DD derived wind speed (m s⁻¹) for a single volume at 150 m height across the experimental domain during the identified (A) unstable and (B) stable periods. The solid black line represents the location of the R3 rotor sweep at x=500 m, y=500 m. Black dots represent the volume one-second turbine inflow extraction points across the rotor sweep at this height. Bottom: Associated wind speed (m s⁻¹) cross-sections at the location of the rotor extraction overlaid by the hypothetical rotor sweeps R1 (black), R2 (red), and R3 (blue) during the (C) unstable and (D) stable periods. Respective rotor centers are denoted by plus markers. Analysis domain grid points are shown as grey dots.
features and generate turbine inflow forecasts of wind speed and direction at each rotor grid point. This method assumes the hypothetical rotor sweeps are perfectly aligned with advection direction of the boundary layer structures in the volume. Extractions from each volume were then stitched together to construct one-second time histories of wind speed and direction information across the various rotor sweeps to be used for further analysis. For example, one-second rotor swept averaged wind speed and direction time histories were constructed to evaluate the general wind speed and direction evolution throughout the analysis period and to highlight differences across the three rotors (Figure 3). Because no other atmospheric measurements were available from the data collection region, atmospheric stability was determined subjectively based on the texture of the wind flow structure as observed in previous remote sensing studies. Indeed, a pronounced evolution in the turbulent features was observed in the DD domain during the experimental period as highlighted in Figure 2A-B. The duration of the complete experimental period was 10,876 s, or approximately three hours spanning roughly 2214 UTC through 0115 UTC, with sunset occurring at 0001 UTC. For the purposes of constructing summary statistics for this study, data between time steps 1000-4000 s were used to represent the unstable period and 6000-9000 s the stable period (Figure 3).

3. Results
Statistics were generated to investigate inflow variability using the constructed one-second time histories. Data were examined both in space and time to compare inflow conditions across the three rotor concepts and between the unstable and stable periods. The various parameters examined will be discussed here and are summarized in Table 2.

3.1 Wind Speed and Direction
To gain a general understanding of the background wind conditions, wind speed and direction data were averaged across each of the three rotor concepts for each one-second time step...
Rotor swept averaged wind speeds ranged from 6.3 – 11.6 m s\(^{-1}\) throughout the experimental period, generally increasing with time as the atmosphere transitioned from unstable to stable. Rotor wind speeds averaged in time over the entire experiment were 9.1 m s\(^{-1}\) (R1), 9.2 m s\(^{-1}\) (R2), and 9.3 m s\(^{-1}\) (R3). During the unstable analysis window, rotor averaged wind speeds for R1, R2 and R3 were 8.2, 8.3 and 8.4 m s\(^{-1}\), respectively, increasing to 9.8, 9.9 and 10.0 m s\(^{-1}\) during the stable period. This increase in mean wind speed with increasing rotor size is expected as the larger rotors extend higher into the boundary layer and therefore might be expected to capture higher momentum in a sheared environment. During the unstable period, fluctuations in wind speed were more pronounced when compared to the stable period as turbulent gusts and lulls in the flow were more evident. For example, the range of R3 rotor averaged wind speeds decreased from 2.4 m s\(^{-1}\) during the unstable period to 1.1 m s\(^{-1}\) during the stable period.

Differences in rotor swept averaged wind direction were also analyzed between the three rotor concepts. Composited over the entire experiment, rotor averaged wind direction increased from 32.2° for R1, to 32.7° for R2 and 33.2° for R3. The trend of increasing rotor averaged wind direction with increasing rotor size was generally consistent throughout the experiment regardless of the stability regime. Similar to wind speed, a noticeable decrease in the range of rotor swept averaged wind direction was documented between the unstable and stable analysis windows, as the range of R3 rotor averaged wind directions decreased from 22.9° to 7.7° for the unstable to stable periods.

Table 2. Rotor sweep summary statistics for the experiment. The unstable period spans time step 1000-4000 s, the stable period 6000-9000 s, and all represents the full 10,876 s experiment.
3.2 Wind Speed Shear and Direction Veer
To evaluate vertical variability of wind speed and direction across the rotor sweep, a one-minute moving average was passed through the one-second time history data for each rotor grid point to smooth smaller turbulent scales. Rotor sweep variability was assessed both in the vertical and horizontal dimensions. Vertical wind speed shear and wind direction veer was assessed by taking the average wind speed across the row of horizontal grid points at the top of the rotor sweep minus the average wind speed across the row of the horizontal grid points at the bottom of the rotor sweep for each time step (Figure 4). Similarly, lateral shear and veer was assessed by taking the absolute value of the average wind speed across the column of vertical grid points on the left of the rotor sweep minus the average wind speed across the column of vertical grid points on the right of the rotor sweep.

Values of vertical wind shear averaged over the full experiment were larger for R2 and R3 when compared to R1 (Figure 4A). Experiment averaged shear increased by 35% between R1 and R2 and by a lesser 11% between R1 and R3. Average vertical shear between the unstable and stable periods increased by 32% for R1, 6% for R2, and decreased by 23% for R3. These results suggest that the maximum wind speed within an average vertical wind speed profile was below the top of the R3 rotor sweep, particularly during the stable period, as a result of a shallow low-level jet feature that developed following the stability transition (Figure 5). The range of vertical shear values between the unstable and stable periods decreased 23% for R1, 9% for R2, and 3% for R3.

When averaged over the full experiment, vertical wind direction veer increased with increasing rotor size, most pronounced during the stable period (Figure 4B). During the unstable period, R2 and R3 experienced nearly equivalent vertical veer and were both greater than R1. However, during the stable period, average vertical veer increased with rotor size with values of 2.0°, 3.7° and 4.1° for R1, R2 and R3, respectively. The range of vertical veer values between the unstable and stable periods increased slightly from 6.0° to 7.4° for R1 and decreased from 12.5° to 9.4° for R2 and from 17.9° to 11.1° for R3.

Averaged over the full experiment, lateral rotor sweep shear doubled in magnitude between R1 and both R2 and R3 (Figure 4C). The majority of this increase occurred during the unstable period as a result of increasing rotor size capturing more horizontal wind flow variability associated with gust and lull features in the boundary layer flow. A rather pronounced evolution of the lateral shear across the rotor sweeps occurred between the unstable and stable periods as turbulent features in the background flow subsided. Lateral shear decreased 76% for R1, 79% for R2, and 78% for R3. The range in lateral shear values calculated throughout the unstable and stable analysis windows also decreased substantially by roughly 80% for all three rotor concepts.

Trends in lateral wind direction veer were similar to those seen in lateral shear (Figure 4D). Lateral veer averaged over the full experiment increased from 0.49° for R1 to 0.76° for R2 and 0.85° for R3. However, significant reductions in lateral veer were found between the unstable and stable periods. Average values decreased from 0.79° to 0.22° for R1, 1.27° to 0.32° for R2, and 1.42° to 0.40° for R3. The range in lateral veer values calculated throughout the unstable and stable analysis windows decreased from 4.86° to 1.65° for R1, 9.67° to 2.25° for R2, and 12.07° to 2.84° for R3.
Figure 4. One-minute moving average time histories of (A) vertical wind speed shear (m s\(^{-1}\)), (B) vertical wind direction veer (deg), (C) lateral wind speed shear (m s\(^{-1}\)), and (D) lateral wind direction veer (deg) for rotor R1 (black dots), R2 (red dots), and R3 (blue dots).

Figure 5. Composite vertical wind speed profiles through the rotor sweep region for the unstable (green) and stable (red) periods. The rotor sweep top and bottom are shown by horizontal lines for R1 (black), R2 (red), and R3 (blue).
3.3 Turbulence Intensity
The ability to extract one-second wind speed time histories at each rotor sweep grid point allowed for an estimate of the TI across the three rotor concepts. Consistent with the previous rotor statistics, a one-minute moving window was passed through each rotor grid point one-second wind speed time histories to generate one-minute mean, standard deviation, and the resulting TI values. To compare the three rotors, TI generated at each rotor grid point was averaged across the rotor sweep to construct rotor sweep composite TI time histories (Figure 6A). As shown in Table 2, values of TI averaged over the stable, unstable, and full experimental period were nearly identical for the three rotor concepts. For R3, rotor composited TI ranged from 4.9% averaged over the unstable period to 2.5% averaged over the stable period. Again, a pronounced reduction in the range of TI values existed between the unstable and stable periods. The range of TI values decreased from 6.7% to 2.5% for R1, 5.4% to 2.2% for R2, and 5.0% to 2.2% for R3. This decrease in range is qualitatively evident between time step 4000 and 5000 in the time history plots, but also by looking at a vertical profile of TI with time. To do this, time by height plots of one-minute rotor wind speed (Figure 6B), wind speed standard deviation (Figure 6C) and TI (Figure 6D) were constructed. A profile was generated at each time step by averaging the mean and standard deviation wind speed across all horizontal grid points at each constant height through the depth of rotor, as shown for rotor R3. Comparing these plots, wind speed through the depth of the profile generally increased with time, particularly during/after the stable transition, while the associated standard deviation decreased. Between time steps 6000-9000 s, the maximum wind speed within the R3 rotor sweep profile was found below the rotor top between 100-200 m, while after time step 9000 s a more uniform (and higher magnitude) wind speed profile was measured. Despite the higher wind speeds measured beyond the 4000 s time step, TI was dominated by the standard deviation of wind speed. Of note, while there was a distinct reduction in TI between the unstable and stable periods, higher TI values were also intermittently evident above ~180 m during the second half of the record (above the jet level). TI values between 5-7% were measured above 200 m, while values below were nominally between 2-4%.

4. Applications
The presented DD radar measurements, analysis techniques and results can be used to inform many aspects of the wind energy community spanning various temporal scales. When data availability is supportive, radar provides rapid scan speeds while maintaining high spatial resolution allowing for the construction of high-fidelity wind speed, wind direction and derived turbulence information over relatively large analysis domains (i.e. tens to hundreds of square kilometres) across the width and depth of the rotor sweep, including the simultaneous examination of the flow across multiple turbine rotors within the DD analysis domain. The measurements presented were collected in the absence of turbines. Should turbines be present, care would need to be taken to first edit and remove “point target” contamination to the measured velocity fields for each radar created by the turbines and their rotating blades. Previous studies have shown that accurate turbine inflow forecasts, generated in a variety of ways, can be generated when turbines are present.2-7 Several operational applications exist depending on the required data availability both in spatial coverage and in time. For example, aggregated over longer time scales, detailed wind information across the rotor sweep can be used to construct more elaborate power curves to monitor the evolution of turbine performance and identify potential issues10. For short term forecasting applications, turbine inflow conditions can be projected in real-time for various forecast time windows (e.g. one-minute, five-minute, etc.) including the advanced detection of significant variabilities associated with wind ramps or lesser gust and lull features inherent to the background wind flow. While a more complicated endeavour, this information may also inform the next generation of turbine controls whereby the turbine has
second-by-second knowledge of incoming wind features at various distances upstream to drive performance optimization decisions.

These techniques can also serve research and development studies such as validation and improvement of various modelling efforts. Second-by-second time histories and/or spatial data fields characterizing the wind variability upstream of a particular turbine can be used to feed and improve various engineering models. Identification of wind speed and direction correlations across growing rotor concepts are of particular importance. The data fields may be of particular value in cases were turbulence is quickly evolving such as a stability transition, where the model uncertainties could be reduced by ingesting a true measured representation of the turbulence that exists. Wake modelling efforts could also be advanced leveraging this high fidelity information. For a given wake snapshot, knowledge of the evolving inflow conditions directly associated with the wake at a particular downstream distance provides for a more representative assessment of the magnitude and dissipation of the wake8.

Figure 6. (A) One-minute moving average time histories of TI averaged across rotor R1 (black dots), R2 (red dots), and R3 (blue dots). Rotor R3 time by height plot of one-minute (B) wind speed (m s⁻¹), (C) wind speed standard deviation (m s⁻¹), and (D) TI (%).
5. Conclusions
Using measurements from the TTUKa radars and associated DD data collection techniques, a detailed characterization of the inflow conditions of three hypothetical turbine rotor concepts was presented through an unstable-to-stable boundary layer transition. High fidelity wind information was extracted from the generated DD volumes using an advanced advection correction technique to generate second-by-second turbine inflow wind speed and direction forecasts for each grid point across the rotor sweep. This study confirms the application of using radar measurements to generate turbine higher resolution inflow measurements and provide insights across varying rotor concepts and stability regimes. However, information from other instruments would have been beneficial to provide further validation and a detailed assessment of uncertainty of both the inflow characteristics and the subjectively determined stability characterization.

As the turbine rotor size increased, so did the vertical wind speed shear and wind direction veer. Lateral increases in wind speed shear and wind direction veer across the rotors was also found with each increasing rotor size as the larger rotor size was more susceptible to experiencing diverse boundary layer gusts and lulls simultaneously across the rotor sweep. A pronounced reduction in this lateral shear and veer variability was measured when comparing the unstable and stable analysis periods. Reductions in both the average lateral shear, as well as the range of values across each period, of roughly 80% were calculated across the three rotor sweeps. While rotor swept averaged TI did not vary considerably between the three rotor sizes, vertical profiles of TI generated for R3 saw reduction from 5-7% during the unstable period to 2-4% for the stable period. Interestingly, during the stable period, intermittent periods of higher TI values above 200 m were documented impacting the top of the rotor R3 concept.

As turbine rotor sizes continue to grow, the results of this study and other future studies, will provide valuable insights into the potential variability of the wind across these larger concepts. Variability in wind speed, direction and TI have direct ramifications on turbine performance and loading. Such studies can directly improve engineering design and contribute to the development of future turbine controls concepts, short-term turbine inflow forecasting methodologies and improvements to turbine loading and wake modeling efforts.

6. References
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