High-resolution Doppler lidar data analyses show that advances in measuring, understanding, and modeling of the atmospheric boundary layer will be required to provide improved meteorological support for wind energy.

Scanning high-resolution Doppler lidar is a remote sensing instrument having the capability to provide high-precision wind speed data at vertical resolutions of less than 10 m through the lowest several hundred meters of the atmosphere. Analyzed lidar data are presented from two field projects in the U.S. Great Plains. This region has high wind energy resource potential and nighttime meteorological conditions that are difficult to understand and model. The major nocturnal wind resource in this region is the low-level jet (LLJ).

Analyses of lidar data reveal many aspects of these flows important to wind energy. For example, the LLJ shape evident in the individual profiles is shown to be poorly represented by standard profiles, such as the power-law profile often used to extrapolate near-surface measurements to hub height. Dealing with the strong spatial and temporal variability of winds in the rotor layer at multiple scales is a challenge that will need to be addressed by multiscale arrays of appropriate profiling instrumentation. Four areas where advancements are most needed are described.

Meteorological variability of the wind resource is an important source of uncertainty in the wind energy (WE) industry. Considering the electric power industry as a whole, its imperative is embodied in the often quoted “priority number one,” which can be stated—when a customer flips a switch, the lights must come on. In other words, by the time the power is dispatched, all sources of uncertainty, including meteorological, must have been resolved. For the WE industry the sources of uncertainty can be purely meteorological, such as predictions of wind and turbulence at various lead times; they can be nonmeteorological, such as the percentage of turbines offline (not operating) at a given time or how much power is required by the electrical grid; or they can be a combination, such as when strong turbulence bursts damage turbines and take them offline or when turbine wake effects reduce the power output.
of downstream turbines in wind farm arrays. Here, we address meteorology-related uncertainties due to the variability of the winds.

Two aspects of the WE industry make it different from most meteorological applications. First, it requires a high level of precision. Errors of less than 1 m s\(^{-1}\) in estimating the annual wind resource for a wind farm can translate into many millions of dollars in annual revenues; other needs for atmospheric information are similarly sensitive. Second, wind information is required in a layer aloft occupied by the turbine-rotor blades, rather than at the surface where the preponderance of measurements is taken. Unfortunately, a scarcity of measurement data of high enough quality to effectively meet the needs of the WE industry exists at the required heights.

Wind energy is an important meteorological application, but it consists of many "subapplications," which we will simply refer to as WE applications for convenience. These WE applications range from hardware design, to resource assessment and "prospecting" for favorable wind farm locations, to siting and construction of wind farms as well as individual turbines, to operations including forecasting and performance of maintenance, through refurbishing and "repowering" of the site for continued operation into the future. Other issues include environmental impacts of wind farms, turbine wake effects on productivity within the wind farm, and rotor-layer wind climatology to determine typical conditions, extreme conditions, or whether the resource is changing over decades (Schreck et al. 2008; Shaw et al. 2009). Although each subapplication may have somewhat different requirements for precision, frequency, or resolution of wind data, they have some basic needs in common, such as a mean inflow wind in the rotor layer, often taken as wind speed at the height of the turbine-rotor hub averaged over 10 min, the magnitude of abrupt changes in wind speed, and peak values of turbulent fluctuations and shear encountered within the rotor layer.

To provide the best wind information, a challenge for meteorology is to characterize the key meteorological phenomena that affect the flows at appropriate time and spatial scales for the application of interest. Understanding such phenomena is obviously important for forecasting—forecasters want to understand what they are predicting. But such detailed characterization is often important for other applications. For example, even though climatology and resource assessment are for longer time periods, accurate climatologies of phenomena such as the LLJ, its properties, and its effects may be needed. Such climatologies would have to be based on profile measurements at high enough precision and vertical resolution to discern the wind speed maximum or jet "nose." Similarly, climatologies of ramps, wind gusts, shear, or extreme events in the rotor layer must be compiled from measurements capable of detecting those events. Thus, fine resolution and precision are required in the measurements even though climatology is a long-term application. Additionally, obtaining needed information for WE industry applications, such as forecasting, modeling, and research, often requires meteorological measurements through a deeper layer than the rotor layer or over a broader area than one measurement site.

The lack of measurement data of sufficiently high quality through and above the turbine-rotor layer means that key meteorological phenomena and processes affecting the winds there are not well characterized or understood. The fidelity of numerical weather prediction (NWP) forecast models in those layers is also not well known, although available evidence indicates errors and uncertainties too large for the WE industry’s needs (Schreck et al. 2008). An important contribution for meteorology is to minimize the uncertainties in wind resource characteristics to the extent possible. To do this will require advances in the state of the art in understanding the lower atmosphere. Recent progress in measurement capabilities makes this a possibility. Here, we describe insights from one advanced sensor, the High-Resolution Doppler Lidar (HRDL), developed and operated by Earth System Research Laboratory of the National Oceanic and Atmospheric Administration (NOAA/ESRL). HRDL provides detailed WE industry-relevant information on the structure and behavior of flow phenomena through and above the turbine-rotor layer.

**NEED FOR APPROPRIATE MEASUREMENT.** Available episodic studies have shown that complex atmospheric phenomena and strong gradients occur in the turbine-rotor layer at length scales as small as a few meters. These phenomena comprise, or control, the inflows to turbines and to wind farms. Mean and fluctuating components of these inflows need to be accurately characterized for most WE industry applications. An important first step, therefore, is to characterize and better understand wind flow features in the rotor layer and their driving mechanisms. This requires appropriate measurements. A recent National Research Council report (NRC 2009) highlights what those measurements might look like. NRC (2009) describes a phenomenological approach to observational requirements, focusing on
high-impact weather phenomena and summarizing the work of T. W. Schlatter et al. (2005, personal communication). According to this approach, each type of weather phenomenon, such as snowstorms, hurricanes, thunderstorms, tornados, etc., has a characteristic longevity and size (time and space scale). Useful sampling of each type of weather system requires measurements at appropriate spatial densities and time intervals, “not only to detect and monitor the phenomenon, but also to describe its internal workings and predict its onset and future behavior” (NRC 2009, p. 26). For example, the twice-daily rawinsonde network is inadequate to characterize the life cycles of thunderstorms and moist convective systems, but the use of sophisticated storm radars led to rapid progress in understanding and predicting these systems in the 1970s and 1980s by providing reflectivity and wind measurements at the required space and time scales.

It could have been anticipated that weather radar would be the right tool for probing moist convective systems because cumulonimbus clouds and thunderstorm complexes are visible, and their characteristic spatial dimensions and lifetimes were well known before radar. On the other hand, phenomena controlling the winds in the turbine-rotor layer are invisible, so that their natures, and sometimes even existence, can only be known through observations of atmospheric quantities, such as wind, temperature, and pressure. Some “high impact” phenomena for the WE industry may include fronts and other density currents, low-level jets, gravity waves, terrain-forced flows, and others, including potentially unknown phenomena. Knowledge of gross spatial dimensions and lifetimes of flow phenomena in this layer is essential, but by itself is insufficient to determine sampling requirements to characterize them. Characterization of the three-dimensional, often transient phenomena that drive the winds in the lowest few hundred meters of the atmosphere requires instrumentation having adequate spatial resolution—especially in the vertical $\delta z$, frequent-enough sampling intervals $\delta t$, and adequate measurement precision $\delta \phi$, where $\phi$ is the quantity being measured—to characterize the phenomena of interest. Other considerations are also critical for vertically profiling remote sensing instrumentation, such as the height of the lowest data point, the maximum range, the availability of useful measurements as a function of height, and, for forecasting applications, the real-time quality of the measurement (i.e., the need for and effectiveness of quality control).

To design a measurement strategy for detecting wind-controlling phenomena in the turbine-rotor layer therefore, one needs to know their spatial and temporal properties and the magnitudes of variability that define them, allowing $\delta z$, $\delta t$, $\delta \phi$, and the other measurement criteria to be specified. Appropriate instrumentation can then be deployed. The dilemma, the catch-22, is that these inputs are unknown because of the lack of measurements, especially routine measurements, above the surface in this layer. The answer to this dilemma would be to oversample—that is, sampling at finer resolution and better precision than required—then using these measurements to back off and determine the lowest resolution needed to characterize flow phenomena of interest. But such measurements may be impractical, expensive, or unavailable, so the practical solution is to use the best available technology.

An instrument that has proven the ability to provide high-resolution and high-precision measurements in the lowest few hundred meters of the atmosphere, precisely where needed for wind energy, is NOAA’s HRDL (Fig. 1). HRDL has participated in several research field campaigns. Analysis of those datasets can provide insight into the structure and...
behavior of flow phenomena affecting wind energy. Although HRDL is a research instrument, the relevance to the WE industry problem is that commercial systems having comparable capabilities have recently come onto the market.

An example of HRDL information is given in Fig. 2 as hourly wind speed profiles at 5-m vertical resolution, showing the evolution of a nocturnal LLJ and illustrating features such as the strong shear in the layer below the LLJ nose. The behavior and evolution of the LLJ and the associated subjet winds for the entire nighttime period are obtained by combining profiles for shorter averaging periods into a time–height cross section (e.g., Fig. 3) through the lowest several hundred meters, which includes the turbine-rotor layer (delimited by the horizontal lines, for a 1.5-MW turbine).

**HRDL CHARACTERISTICS AND DATA ACQUISITION.**

HRDL is a scanning, pulsed, coherent, remote sensing, laser-based wind measurement system (Grund et al. 2001; Wulfmeyer et al. 2000) in its second decade of providing high-quality wind measurements through the lowest several hundred meters above Earth’s surface. This paper will emphasize the use of HRDL as a wind profiling device. Unlike most wind profiling remote sensors, which cycle among several (typically three or five) high-elevation pointing angles, HRDL profiles are calculated from scan data typically at low-elevation angles, providing data within meters of the surface and preserving measurement precision for the horizontal component. As shown in Fig. 4, and described in “Profiling,” two types of lidar scan are used to compute profiles: 360° azimuth scans, which produce cones of atmospheric data, and elevation scans, which generate vertical slices of data. The “Profiling” sidebar provides a brief outline of how profiles are calculated.

An important consideration is that profiles from scan data already are precise estimates of the winds as a result of being averaged spatially, allowing fine time resolution for investigation of nonstationary

**Fig. 2.** Hourly vertical profiles of horizontal wind speed from HRDL conical scans showing evening development of the LLJ near Lamar, CO, on 15 Sep 2003. Wind speed (m s\(^{-1}\)) on horizontal axis, and height (m) on vertical axis. Profiles are color coded by time (UTC), which is 7 h ahead of local (mountain) standard time, so that 0100 UTC is about sunset and 0700 UTC is midnight. Vertical resolution is 5 m. Turbine-rotor layer is indicated by horizontal dotted lines. (Figure courtesy of the American Meteorological Society.)

**Fig. 3.** Time–height cross section of (top) mean wind speed \(U\) for 15 Sep 2003; same night as in Fig. 2. One-min profiles are color coded according to \(U\) (m s\(^{-1}\)). Black plus signs show height of LLJ nose. (bottom) Time–height cross section of streamwise variance \(\sigma^2\), with 1-min profiles color coded according to variance \(\sigma^2\) (m\(^2\) s\(^{-2}\)). Black symbols indicate \(h_{SBL}\) diagnostics described by Pichugina and Banta (2010), and red symbols show \(h_{SBL}\) as a minimum in the \(\sigma^2\) profile. Turbine-rotor layer indicated by horizontal black lines.
phenomena having time scales of a few minutes. For example, conical scans take approximately 2 min to complete and vertical slice scans can be completed in 20–30 s, to yield accurate profiles at these time intervals. The random error in the mean values can be further reduced by averaging over longer periods, such as 5 min or 1 h. The main concern for the averaging period is finding intervals long enough to achieve the required precision, yet short enough so the flow can be considered stationary. Intercomparison studies against tower-mounted anemometer data reinforce that Doppler lidar is a precise way to measure winds (Hall et al. 1984; Grund et al. 2001; Smith et al. 2006; Kindler et al. 2007; Peña et al. 2008, 2009; Mann et al. 2010; Drechsel et al. 2012; Pichugina et al. 2008, 2012; Kelley et al. 2004, 2007; Tucker et al. 2009). For example, Pichugina et al. (2008) found high correlations between lidar-measured mean wind speed and turbulent variances from scan data and those measured by anemometer for 5-m vertical and 5-min averaging (good correlations were also noted for 1-m and 1-min averaging). These studies have reported mean velocity precisions of less than 5 cm s\(^{-1}\) for such averaging parameters. Taken in their entirety, these profile capabilities for vertical resolution, frequency, precision, and height of the lowest data represent a significant advancement over other available remote profiling techniques through the lowest several hundred meters of the atmosphere. The measurement capabilities of scanning, pulsed Doppler lidar, as described here, are a good match for the WE industry’s needs because resolution and precision of this kind are needed to characterize and understand phenomena affecting the flow in the rotor layer.

**WIND PROPERTIES IN THE ROTOR LAYER.** HRDL datasets can be used to provide insight into the kinds of flow phenomena controlling the winds in the turbine-rotor layer, from which we can determine instrument requirements. The evening LLJ profiles in Fig. 2 and time–height cross sections of the nocturnal flow evolution in Fig. 3 provide examples of the type of information available from this kind of high-resolution lidar.

An important characteristic of winds in the turbine-rotor layer is the strong diurnal signature. This means that atmospheric interactions between this layer and Earth’s surface are important in forcing the evolution of the winds at rotor altitudes because the diurnal cycle is ultimately driven by the surface daily heating and cooling cycle (see “Diurnal cycle” for more information). It also means that NWP models must get these atmosphere–surface interaction and mixing processes right, which requires improving the representation of turbulent mixing and other physical processes in the models (Seaman 2000; Dabberdt et al. 2004). Understanding and predicting winds in the rotor layer will require accurate representation of diurnally modulated boundary layer (BL) processes.

![Scan pattern for conical azimuth scans at three elevation angles.](image)

![Successive vertical slice scans showing LLJ structure and vertical binning technique.](image)

**Fig. 4.** (a) Scan pattern for conical azimuth scans at three elevation angles. Color-coded radial velocity data are shown projected onto the cone opening, with warm colors indicating flow away from the lidar and cold colors toward. (b) Successive vertical slice scans showing LLJ structure and vertical binning technique. Vertical axis is height (m), perpendicular horizontal axis is horizontal distance from lidar (km), and angled “out of page” horizontal axis represents time displacement of scans, with scans starting at ~30-s intervals (data from each scan presented as if simultaneous). (Figure courtesy of the American Meteorological Society.)
HRDL is equipped with an azimuth—elevation scanner. Scanning in azimuth at fixed elevation generates a cone of Doppler radial velocity measurements from the atmosphere. Scanning in elevation along a constant azimuth produces a range-versus-height cross section or vertical slice of radial velocities. Both types of scan are used to calculate vertical profiles of the horizontal wind. From the conical scans, profiles are calculated using the velocity–azimuth display (VAD) technique (Lhermitte and Atlas 1961; Browning and Wexler 1968). Each range gate traces a constant-height ring as the lidar scans through 360° of azimuth, and the wind speed and direction are determined for each ring by fitting a sine wave to the radial velocities as a function of azimuth. The wind speed and direction values form a profile because the data rings at greater range are at higher altitudes. For a scan at 2° fixed elevation, the vertical separation between the 30-m slant-path range gates is 1 m. At 10°, the vertical resolution is 5 m, but the profile extends higher into the atmosphere. Customarily, we perform conical scans in sequences, such as 2°, 5°, and 15° elevation, to maximize the vertical resolution near the surface but provide vertical extent (Fig. 4a). Note that despite the 190-m minimum range, the first wind measurement for a 2° scan is at 6.6 m. Depending on the scanning speed selected, each conical scan takes 1–2 min to complete. At two pulses per second, these represent 120 and 240 values in the VAD averaging, improving the precision of the mean estimate by factors of 11 and 15.5, respectively. This reduces the uncertainty in the means due to random instrumental noise to less than a few centimeters per second, meaning that the variance of these mean values is dominated by atmospheric variability, which is typically much larger, rather than instrument limitations.

Profiles at finer time resolution can be obtained from vertical slice scans aligned along the mean wind direction, which take 20–30 s to complete (Banta et al. 2006; Pichugina et al. 2008). These scans are analyzed by dividing the scan into bins in the vertical, as shown in Fig. 4b. Bins are typically 5 or 10 m thick, but vertical intervals as small as 1 m have been successfully used (Pichugina et al. 2008). Fine-resolution averaging in time and in the vertical can be achieved from scan data because each mean value represents an average in space (horizontal) as well as time. Over relatively even terrain, this technique also produces profiles of the streamwise component of the turbulent variance (Banta et al. 2006; Pichugina et al. 2008; Tucker et al. 2009).

Extensive comparisons of HRDL mean wind values against tower-mounted sonic anemometer data for the same averaging periods exhibited very high correlations (Pichugina et al. 2008).

Comparisons such as these establish scanning Doppler lidar as a precise wind profiling instrument.

The ability to calculate profiles from scans at low-elevation angles provides another advantage in measurement precision. A factor for all wind profiling instruments operating at large elevation angles is that the projection of the horizontal wind component $V_h$—the desired measurement—onto the measured radial Doppler wind $V_D$ is relatively small. Considering the case where the azimuth of the measurement beam is aligned along the mean wind direction and (ignoring the $w$ contribution to $V_D$), the horizontal wind component is calculated from the measured wind by $V_h = V_D / \cos \theta$, where $\theta$ is the elevation angle, or by $V_h = V_D / \sin \zeta$, where $\zeta = (90° - \theta)$ is the zenith angle. The horizontal velocity is increased by a factor of $1 / \cos \theta$ over the measured $V_D$ component. For an elevation angle of 75°, for example, $\cos \theta = 0.259$ and $1 / \cos \theta$ is about equal to 4, so a measured value of 2 m s$^{-1}$ would correspond to a horizontal component of $V_h = 8$ m s$^{-1}$. If we further consider the uncertainty or precision $\varepsilon_V$ of $V_D$, then the precision of the estimate of the horizontal component is similarly increased by a factor of $1 / \cos \theta: \varepsilon_{V_h} = \varepsilon_V / \cos \theta$. Thus, an uncertainty of 0.3 m s$^{-1}$ in the measured $V_D$ is augmented to an uncertainty of $1.2$ m s$^{-1}$ in $V_h$ at 75° elevation because of the geometry. At low elevation angles, this augmentation is minimal.

The diurnal cycle of winds at different vertical levels can be illustrated using anemometer measurements from a tall tower. Figure 5 shows wind speed data over two midnight-to-midnight diurnal periods from a 120-m tower near Lamar, Colorado, in the grass-covered, gently rolling terrain of the U.S. Great Plains. The near-surface winds at 3 m above ground (blue trace) were 4–6 m s$^{-1}$ or less without much day–night difference. Occasional lulls occurred especially near dawn and dusk. During daytime, the winds aloft at 52 m (black trace) and 113 m (red trace) tracked the surface winds closely and showed small differences in the vertical (weak shear). This strong coupling between wind speeds at the different levels is an expected result of surface heating and strong BL mixing. At night, however, the winds at 52 and 113 m accelerated as part of LLJ formation (see the “Diurnal cycle”), a strengthening not reflected at the surface. Such decoupling of near-surface winds from those aloft is a common characteristic of the stable nocturnal BL. This characteristic makes it difficult to apply standardized profiles in the calculation of winds aloft from near-surface measurements.

Important finescale structures can affect wind forecasts at all hours of the day, but some of the most important findings from studies using HRDL have involved the nocturnal LLJ and the stable boundary
When winds at any level in the lower troposphere exhibit a diurnal cycle, interactions with the surface are important at that level because diurnal cycles are ultimately driven by the daily heating–cooling cycle at the surface.

From basic principles, the diurnal heating–cooling cycle in cloud-free conditions starts at the Earth’s surface, which acts as a source (day) or sink (night) of heat to the atmosphere. The heating or cooling transfers upward, most efficiently by turbulent mixing, longwave radiative flux divergence, or microscale or mesoscale ascent. The occurrence of a diurnal cycle up to a level is thus an indicator of the importance of interactions between the atmosphere at that level and the surface (ignoring contributions from radiation-absorbing aerosol and gases). The rate of vertical transport, which is variable in time and space, is key because it controls the profile shapes, including gradients of wind (shear) and temperature (lapse rate). The gradients in turn determine the Richardson number $R_i$ [where $R_i = g(\Delta \ln U/\Delta z)(\Delta U/\Delta z)^2$] and thus control the dynamics of layers exhibiting diurnal cycles. These processes feed back as a loop, since the gradients and $R_i$ determine turbulence levels and the rate of vertical transfer. In addition to governing local dynamics and profiles, these transfer processes also force a range of diurnally varying flows, including sea breezes, slope and valley flows, and low-level jets.

This elementary discussion highlights the importance of vertical transfer processes, but these processes are not well characterized or understood, especially during nocturnal and other stable conditions. Consequently, they are an acknowledged weakness in NWP forecast models (Seamen 2000; Dabberdt et al. 2004). These shortcomings can introduce significant errors into the simulated structure and dynamics of the lowest atmospheric layers, through at least the lowest few hundred meters (Zhong and Fast 2003; Storm et al. 2009). In particular, limitations in the representation of stable processes introduce uncertainty into each model prediction interval that includes nighttime periods or transition periods between day and night.

Forecasters count on the models for predicting future states of the atmosphere, including winds above the surface. They rely on these models for predictions having lead times of more than a few hours. But if the prediction period includes transitions or nighttime intervals, the poor representation of physical processes, such as stable mixing, makes it difficult to have confidence in the model guidance, especially for applications requiring accurate quantitative information. It is a significant challenge for models to produce accurate quantitative predictions of wind speeds, shears, and turbulence magnitudes at turbine-rotor heights using current state-of-the-art physical parameterizations of turbulent processes (Storm et al. 2009).

Making accurate quantitative predictions of meteorological variables and the timing of changes, including those occurring during morning or evening transitions, is a significant challenge for current-generation models, made even more difficult by the lack of appropriate measurement datasets to diagnose, in a useful manner, where models need improvement.

**DIURNAL CYCLE**

![Graph](image-url)
The importance of stable processes lies in the fact that the nighttime period occupies about half the diurnal cycle, during which time the wind speed resource in the rotor layer tends to be strongest. But the nighttime vertical structure and the rate of vertical transfer through the lowest several hundred meters—including the layer that directly affects wind turbine operations—are not well characterized, understood, or modeled (e.g., Mahrt 1998, 1999; Poulos et al. 2002; Poulos and Burns 2003; Banta 2008; Fernando and Weil 2010). Anecdotal experience and available evidence (e.g., Storm et al. 2009) indicate that NWP models have considerable difficulty in reliably predicting these LLJ properties or other aspects of the SBL, especially given the accuracy requirements of the WE industry. LLJ structure is also observed in complex terrain (Post and Neff 1986; Banta et al. 1999, 2004; Darby et al. 2006; Cuxart 2008) and offshore (Smedman et al. 1993, 1997; Tucker et al. 2010; Colle and Novak 2010; Pichugina et al. 2012).

Outstanding SBL issues include the shape of the wind speed profile, characteristics of sudden wind speed changes in the rotor layer, and LLJ evolution from night to night. Here, we review these issues based on HRDL profile data from two field programs in the U.S. Great Plains: the 1999 Cooperative Atmosphere–Surface Exchange Study (CASES-99) in southeastern Kansas in October 1999 (Poulos et al. 2002; Banta et al. 2002) and the Lamar Low-Level Jet Program in southeast Colorado in September 2003 (Kelley et al. 2004).

**Profile shapes.** At night the SBL and accompanying LLJ structure and dynamics are compressed into a shallow layer—shallower than the daytime BL by at least a factor of 10—which must be accounted for in specifying instrument requirements. The shape of the wind profile through the rotor layer gives quantities such as height and speed of the jet maximum, depth of the SBL $h_{SBL}$, shear, and the error involved in using standardized profiles, for example, the power-law profile. HRDL analyses have shown the meteorological importance of such profile features. The LLJ wind speed maximum nearest to the ground is an important driver of SBL processes and rotor-layer flow, and the speed and height of the jet are important velocity and length scales in the SBL (Banta et al. 2006; Banta 2008). Recent work

![Figure 6](https://example.com/fig6.jpg)  
Fig. 6. Two examples each of the three basic types of mean wind speed profiles identified by Pichugina and Banta (2010), as observed with HRDL measurements during the CASES-99 and Lamar experiments. Black lines indicate measured wind speed profile, and asterisks show LLJ nose. Type 1 profile is the maximum or nose type. Type 2 profile has a flat profile above the surface-based shear layer (i.e., constant speed with height above the strong-shear zone), as the entire LLJ layer undergoes a constant acceleration after sunset. Type 3 profile has a layered structure to the shear and turbulence below the first wind speed maximum. Also shown are power-law profiles for exponents of 1/7 (red) and 0.3 (blue) starting from the lidar-measured wind speed value at 10-m height. Abscissa is wind speed from 0 to 25 m s$^{-1}$, and ordinate is height AGL. In the calculation of rotor-layer or hub-height winds, such comparisons with measured wind profiles calls into question the advisability of requiring very precise near-surface wind measurements, then estimating the upper-level winds using an extrapolation formula that may introduce errors of several meters per second.
(e.g., Wagner 2009, 2011) has shown advantages in using vertically weighted mean wind speeds across the rotor layer, rather than at one level (such as hub height), for estimating resources and power curves, but high-precision measurements at multiple levels in the rotor layer are required. Although emphasis here is on the nocturnal SBL, note that instrumentation that adequately samples nocturnal conditions will also sample daytime and transitional periods well.

HRDL-measured nocturnal wind profiles have many different shapes; Fig. 6 shows three common shapes identified by Pichugina and Banta (2010). All three types of profile result from an evening acceleration of BL flow over daytime values, so all three are defined as LLJs in that study. By this definition almost all profiles exhibited LLJ structure during stable, cloud-free, nocturnal conditions for jet speeds greater than 5 m s\(^{-1}\). On the night in Figs. 2 and 3, most profiles exhibited the distinct LLJ nose (as in Fig. 6, top), but at times the profile may have two or even more maxima (Banta et al. 2002). The speed maximum that impacts the WE industry most is the lowest one that caps the surface-based layer of strong shear, generally corresponding to the top of the SBL \(h_{SBL}\) (Pichugina and Banta 2010). Profile measurements must thus have sufficient detail to show properties of this LLJ nose, which occurs in the lowest few hundred meters above ground level (AGL) but often can occur at about 90 m above the surface (Banta et al. 2002; Kelley et al. 2004; Kelley 2012).

Similarly SBL depth \(h_{SBL}\), a traditionally difficult, inaccurate measurement (Steeneveld et al. 2007), was significantly improved using HRDL measurements (Pichugina and Banta 2010)(see symbols on Fig. 3). The determination of shear, also difficult because of the high precision required to calculate difference quantities, can be done accurately using high-precision lidar measurements. Banta et al. (2003) found values near 0.10 s\(^{-1}\) during CASES-99, also reported in tower data by Sun et al. (2012), and similar values were also found during the Lamar project (Fig. 7).

Standardized wind speed profiles, such as the power-law profiles superimposed on Fig. 6 (colored curves), are often used to extrapolate near-surface anemometer measurements upward to estimate wind speeds in the rotor layer. Anemometers provide high precision, and measuring winds near the surface with anemometers is cheaper than measuring winds aloft. But for short-term averaging (<1 h) the upward extrapolation can introduce errors of several meters per second, as illustrated in Fig. 6, where sample power-law profiles (blue, red) are superimposed on HRDL-measured profiles (black curves). The calculated profiles start arbitrarily from a height of 10 m, but the key aspect of this figure is that the calculated profile shapes differ significantly from the measured profiles. The conclusion that significant error is introduced into short-term estimates of rotor-level wind speeds by using standardized profiles would also hold for other profile starting points up to 60 m or more. This figure also shows that the measured profile shapes show little resemblance to each other, suggesting pessimism over finding generalized profile functions. These findings were also evident in offshore profiles (Pichugina et al. 2012). Measured winds through the rotor layer of acceptable precision should be preferred.

Some successes have been reported fitting diabatic profiles to measured profiles (e.g., Peña et al. 2008) for long-term averages (e.g., monthly, seasonal, annual). However, the availability of direct measurement data of rotor-layer wind speeds means that annual probability distributions of accurate short-term (e.g., 10 min)
Wind speed values could be used to estimate annual power production with little more computational effort than calculating annual mean winds. Such a procedure would account for the fact that wind speeds greater than average make the dominant contribution to energy produced because of the nonlinear (cubic) relationship between power production and wind speed.

**Night-to-night variability.** The nightly evolution of the mean wind profile, important for forecasting and NWP verification, is often more complex than the steady LLJ accelerations shown in Fig. 2. The four panels of Fig. 8 show different evolution patterns in the hourly profiles from different nights. Such night-to-night variability is strong, even on consecutive nights, as shown in the time–height cross sections of Fig. 9, for four of five successive nights (excluding one rainy night). This variability is a significant challenge for NWP models, which must get LLJ properties right for accurate day-ahead nocturnal wind speed forecasts in the rotor layer. Low confidence in
forecasted nocturnal wind speeds, associated with the large uncertainties in forecast model predictions of LLJ and rotor-layer wind speeds, is a probable factor in the curtailment and underusage of the nighttime resource (Marquis et al. 2011). Moreover, errors in model predictions of nighttime SBL structure imply that the “initial state” for the following morning is also inaccurate, leading to the propagation of uncertainties into the next day.

Within-night variability. Data from HRDL also show many kinds of within-night variability. Dawn and dusk transitions are periods of significant unrest in the winds, especially aloft. In the morning, nocturnal inversion breakup after sunrise often brings a rush of momentum down from aloft, producing rapid increases in wind speed and turbulence (e.g., Banta 1984, 1985, 1986). The evening transition is shown in Fig. 10, a sequence of HRDL scans illustrating the establishment of the LLJ after sunset often characterized by turbulent surges and dips in wind speed potentially damaging to turbine hardware. On the second night in Fig. 9 an obvious phenomenon is a deep, fast-moving cold-frontal passage at 0800 UTC, an example of a sudden wind speed increase, or ramp, detectable in surface measurements. Other types of ramp, either increases or decreases in wind speed, may not be reflected in surface measurements, especially at night. Time series of HRDL wind speed data (Fig. 11) are an effective way to detect such variations. Figure 11 shows abrupt changes in wind speed, which may reach several meters per second over an hour or less, at heights within the rotor layer. Ramps or trends in the winds aloft are often decoupled from those near the surface, for example, around 0200 and 0500 UTC in Fig. 11a or after 0600 UTC in Fig. 11b. Similar behavior is also observed offshore (Pichugina et al. 2012). The important questions are these: What are the phenomena producing these up or down ramps, and can they be tracked or otherwise predicted? If not, what is the uncertainty imposed on predictions?

To answer these questions, appropriate measurements are required to detect and understand the phenomena responsible.

The point of these examples is that high-precision measurements, at sufficiently high vertical resolution and frequent time intervals, can discern detailed temporal changes and vertical structure of the flow. Knowledge of these is important for many WE applications and for BL characterization. Advancement of the state of the art will require much-improved characterization and understanding of many of these flow phenomena and details. Criteria for characterizing meteorological phenomena observed by HRDL, as described in this section, are summarized in Table 1.

The lowest LLJ maximum, which controls the winds in the turbine layer at night, varies from night to night and within nights, but this is not well measured by currently deployed instrumentation. Thus, it is not well represented in datasets (including reanalysis datasets) or model output. Therefore, rotor-layer wind information currently available from existing datasets for the nocturnal portion of the diurnal cycle must be viewed with skepticism.

**WE INDUSTRY REQUIREMENTS AND HIGH-QUALITY MEASUREMENTS OVER AN AREA.** The previous section showed the value
of site-specific, high-precision, high-resolution profile measurements in characterizing meteorological phenomena and processes at a given location of interest. Multiple sensors of this type distributed over an area, which may be several hundred square kilometers surrounding a wind farm or the size of a midwestern state such as Iowa or larger, provide additional advantages in characterizing flow properties. Recent improvements to commercially available scanning Doppler lidar systems make such multiple deployments attainable.

Forecasting, often thought of as the “bread and butter” of meteorology, is a critical need for the WE industry on many time scales, especially the “hour ahead” and the “day ahead” time frames. The hour-ahead forecast (lead times of roughly 15 min–2 h) is used in scheduling power for delivery from a wind farm to the electrical grid. Hour-ahead forecasts thus directly affect the integration of the wind resource into the grid. Errors in forecasts of power supply result in costly penalties (Marquis et al. 2011). Forecasts for such short lead times, or nowcasts, are often be effectively detected and tracked through surface measurement arrays (Parks et al. 2011; Mahoney et al. 2012), so profiling instrumentation may not be needed. Other phenomena, such as those related to diurnal transitions, LLJs, or topographic effects, require more detailed information on atmospheric dynamic and thermodynamic structure vertically and horizontally. Improvements to the hour-ahead forecast will require improvements to the sensor deployment measuring atmospheric properties through the rotor layer. Areawide deployment of advanced-profiling measurement systems, as described here (Table 1), will improve the ability to detect, track, characterize, and understand these phenomena, significantly improving the hour-ahead nowcast.

The day-ahead forecast (roughly 12–36+ hours) is used to save resources by reducing use of carbon-based power sources. It takes some time to ramp sources, such as coal-burning power plants, back up (e.g., Marquis et al. 2011), so turning them down requires confidence in the forecast. Forecasts of more than a few hours, including the day-ahead forecast, generally
involve a diurnal transition, a fundamental change in the physical processes governing the interaction between the winds above the surface and the surface itself (see the “Diurnal cycle”). The forecasts may also involve the advance of larger-scale weather systems. Thus, they are not a simple extrapolation of current conditions. NWP models, meant to capture these changes in physical processes, are used as guidance in formulating these forecasts. The day-ahead forecast, in other words, is most likely a model-based forecast, so forecast improvements will require improvements to models. More accurate representations of mixing and other physical processes are critical to better model predictions (Seaman 2000; Dabberdt et al. 2004; Storm et al. 2009; Schreck et al. 2008).

Although day-ahead forecasts are generally based on NWP models, profile measurements deployed over a region would have important roles in both real-time and postanalysis, where postanalysis refers to a comprehensive, after-the-fact analysis of an event or a case study after gathering all available data. These roles include model initialization, real-time forecast adjustments to the model output, model verification, postanalysis (including “bust analysis”), and model improvement. All require accurate data for the turbine-rotor layer. Using the LLJ–SBL as a specific example, sensors having HRDL-like capabilities (Table 1) distributed over an area would be valuable in real time for accurate initialization (including assimilation) of LLJ properties. That is, accurate \( h_{SBL} \), speed and height of the jet, and other wind profile properties would be properly represented in the initial conditions of the model runs. For simulations that begin during the daytime and continue into nighttime, the progress of the simulation can be tracked by a forecaster and deviations of measured values from the predictions noted, so that wind predictions can be adjusted. Improved understanding of processes controlling the winds in the turbine layer would give forecasters greater confidence in adjusting, localizing, or otherwise tailoring the model output to improve the forecast.

Postanalysis is an important aspect of operational forecast improvement, especially when forecasts do not verify, that is, for “busted” forecasts. Here, it is important to have a comprehensive enough dataset to determine what really happened in the atmosphere, causing the bust, and for model predictions, to determine what the model missed. This is where resolution and frequency of data are important, as in the HRDL examples. Here, too, it is significant that the lidar originally produces scan data and scan images (e.g., Figs. 4 and 10), from which the profiles were calculated. Such scan images have been very useful for interpreting the prevailing meteorological conditions, thus making the lidar dataset even more valuable. Another postanalysis tool is running models retrospectively, to try different modeling approaches. High-resolution profile data at multiple locations over an area would be very useful for initialization and validation of retrospective modeling. For example, if mesoscale NWP models had vertical grid intervals too coarse to resolve the boundary layer or LLJ structure, higher-resolution runs over more limited domains would allow evaluation of the effects of model resolution, but such model studies are only useful to the extent that datasets based on high-quality profile measurements are available for comparison.

The need for reliable information in the rotor layer would benefit other aspects of the WE industry, as can be illustrated by the LLJ–SBL example. Resource assessment often relies on vertical extrapolation of near-surface wind data or on NWP model output, both shown to have large uncertainties during stable conditions. Similarly, siting decisions, whether at the wind plant scale or the individual-turbine scale, and hardware design are often based on similar information. Turbine-array effects internal to the wind farm, used to design the layout of the farms, are often assessed using wind tunnel or numerical studies, which need to be verified for real-atmosphere conditions. Better observations in the appropriate regions of the atmosphere may avoid costly misjudgments.

Environmental impacts, or external effects of turbine arrays on the surrounding countryside downwind, include enhanced turbulent mixing and retardation of the flow (Smith 2010). One of the important impacts is likely to be on vegetation, for example, through drying, warming, or extended growing seasons. Any detrimental impacts could be an obstacle to WE industry development in some regions. The critical questions concerning mixing

### Table 1. Instrument requirements for vertical-profile sampling.

<table>
<thead>
<tr>
<th>Profile criterion</th>
<th>Minimum requirement—less than</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical resolution ( \delta z ) (m)</td>
<td>10</td>
</tr>
<tr>
<td>Sampling interval ( \delta t ) (min)</td>
<td>3</td>
</tr>
<tr>
<td>Velocity precision ( \delta U ) (cm s(^{-1}))</td>
<td>5</td>
</tr>
<tr>
<td>Height of lowest measurement (m AGL)</td>
<td>30</td>
</tr>
</tbody>
</table>
Based on HRDL findings such as those described, we have identified four areas where work is needed to advance the state of the art to where it can adequately support the WE industry: instrument assessment and site design, measurement array design, advancing understanding of meteorological processes through the rotor layer, and NWP improvement.

**Instrument assessment and site design.** Designing a measurement site having an appropriate mix of instrumentation to address the WE industry’s needs requires knowledge of the capabilities of candidate component measurement systems. At a minimum, each site obviously must have wind profiling capability, as specified in Table 1, through the lowest few hundred meters above ground. Also essential are a surface flux site; temperature profiles having accurate vertical gradients for understanding the dynamics of the flow; and moisture profiles, which may be important for predicting clouds and icing (these capabilities are not discussed here). The key aspect of measurement site design is instrument selection. For wind profiling a number of options exist, including radar (profiler), sodar, and various types of lidar. The question is, which are good fits for sampling the phenomena important to the WE industry, since all systems are not equivalent?

HRDL measurements, which have been verified against tower anemometer data (Pichugina et al. 2008), have profile data of sufficiently high precision, resolution, and frequency to document many finescale flow phenomena and yield other important quantities such as shear and $h_{s_{	ext{BL}}}$. Other profiling techniques should be similarly evaluated, since available information on the different types of sensor can be confusing. For example, stated precisions may be based on different averaging intervals, and may be determined during periods of good instrument performance. What is needed are careful objective intercomparison studies among all candidate sensors over extended time periods, perhaps a year or more, to see which are a good match for the WE industry’s requirements and what their roles might be.

Determining appropriate instrument specifications is an important aspect of site design, but other factors are important in optimum site design. For example, for forecasting, resource assessment, and proper climatologies, the site must provide profile data in all weather conditions. Each profiling technology has advantages and limitations. A scanning pulsed Doppler lidar has the advantage of high precision and resolution; a limitation is that the lidar signal is attenuated in fog and low cloud (liquid

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1 In most regions fog is a light-wind phenomenon, so the performance of lidar in fog would not be a significant limitation for the WE industry’s applications.
water), limiting its range. For all-weather operation, therefore, equipping some or all of the profiling sites with sodar and/or radar may be necessary to obtain some data during periods of fog or low clouds, despite the apparent redundancy of measurements. The goal of site design, an ongoing, evolving process because of continually advancing technology, is to specify an appropriate mix of instrumentation to provide profile and surface information for effective WE industry planning and operations.

**Measurement array design.** Individual profiling sites having an appropriate mix of instrumentation would be deployed in arrays or networks. To account for the interacting scales of motion of phenomena affecting winds in the rotor layer, and to provide data for the multiple WE applications, nested arrays are required. An example of a potential design suggested by Banta and Pichugina (2010) and Banta et al. (2010) is shown schematically in Fig. 12a. Deployments of instrument arrays for demonstration projects should be for at least a year, followed by permanent operational measurement arrays.

The outer array of profiling sites is a **regional array** to document larger-scale horizontal gradients and the larger-scale meteorological context. This array provides early detection and tracking of rotor-level ramp events and measurements to see whether the day-ahead NWP predictions are verifying. The array spacing is similar to the U.S. 449-MHz National Profiler Network (NPN) of radar–wind profilers, so augmenting those sites with high-resolution profiling at the lower levels to make up for the coarse (100+ meters) vertical resolution of the NPN instruments is a possibility. Regional arrays from neighboring wind farms would overlap, so the same regional array could serve nearby facilities. A national-scale profiling network having adequate low-level resolution, if instituted, would serve this purpose.

The **local array** would be designed specifically to address the hour-ahead nowcast, but it would also address other important issues, such as spatial variability and representativeness, and effects of the wind farm on the flow. This array is envisioned as a ring of sites, approximately an hour out from a wind plant (or whatever the required forecast lead time is for appropriate propagation speeds), to provide timing and magnitude of features tracked through the regional array. The inner **turbulence array** would detect significant potentially damaging turbulence bursts or events, raising the possibility of operational responses to mitigate these effects. It would also provide information on flow variability, measurement representativeness, and wind farm impacts on the nearby environment.

The **main site** would provide an accurate inflow profile to the wind farm, thus serving as a verification site for NWP forecasts. Different sites from the turbulence array could be the main site for different wind directions. Note that if enough wind farms had high-resolution, high-quality, well-exposed

![Fig. 12. (a) Example of a nested-array configuration for profiling sites. (b) Example of how adjacent arrays, or a national profiling network, could provide regional array coverage. Dashed orange ellipse shows location of array in (a).](image-url)
profiling sites of this kind, and were willing to make the information available, these sites could comprise a regional array or serve as components of other nests (cf. Fig. 12b), to the benefit of all concerned.

**Advance understanding of meteorological processes.** Once profiling arrays are deployed, they will be providing data aloft at densities in space and time not previously available for extended time periods, which should be used in studies to improve understanding of meteorological processes. Because such datasets have been unavailable, a considerable “discovery” aspect still exists for meteorological phenomena and processes in this layer. For example, in studying wind speed spectra and vertical velocity–temperature (w–T) cospectra in stable conditions, Mahrt and Vickers (2006) and Vickers and Mahrt (2003, 2006) clearly identify a turbulence frequency regime, but they also identify scales of lower frequency than turbulence, which they refer to as random mesoscale perturbations or, less formally, “mesoscale junk,” of variable frequencies. Many of these perturbations of as-yet uncharacterized flow features may be wind energy “ramps.” It is unlikely that these phenomena materialize and disappear in place—they have lifetimes, life cycles, dimensions, and propagation velocities, which could be studied by appropriate profiling arrays. As another example, the dominant dynamics of the Great Plains LLJ itself are still controversial, candidates being the decoupling effects of surface cooling (Blackadar 1957; Lundquist 2003), the westward terrain slope of the Great Plains (Holton 1967; McNider and Pielke 1981; Parish and Oolman 2010), the blocking effect of the Rocky Mountains (Wexler 1961), and combinations of these (Zhong et al. 1996; Jiang et al. 2007; Shapiro and Federovich 2009). A problem with using NWP models to sort out the processes is that the relative role of the cooling–decoupling mechanism depends critically on getting the magnitude and vertical variation of the turbulent mixing right. Studies using high-quality profiling arrays will rapidly increase our understanding of phenomena and processes above the surface, including LLJ and SBL dynamics.

**NWP improvement.** More accurate and dependable NWP output would be a significant benefit to all WE industry applications (Schreck et al. 2008; Shaw et al. 2009), especially given the expense of obtaining high-quality measurement datasets. The key question here is, how does the virtual meteorology generated by models relate to that occurring in the atmosphere? A purpose of high-quality measurement arrays should be to specify as completely as possible the three-dimensional state of the atmosphere for successive time periods (at perhaps 10- or 20-min intervals) to initialize (assimilate) and verify model output. Detailed data allow detailed verification of model output, as described by Zhong and Fast (2003), Fast and Darby (2004), Darby and Poulos 2006, Darby et al. 2007, and Banta et al. (2010, 2012). These studies show that verification can be detailed enough to reveal which processes models are capturing well and which need improvement. Ideally, comparisons would also provide insight into the nature of the needed improvements, for example, Are the surface fluxes and vertical gradients well predicted, or do the depths of the nocturnal inversions and the heights of the LLJ show reasonable growth rates and proper variation in the horizontal through nighttime periods? Array datasets would be useful for process studies to improve model physics parameterizations, and the arrays could serve as the backbone of more intensive campaigns targeted at specific parameterization improvements (e.g., LeMone et al. 2000; Poulos et al. 2002). Such studies can address the minimum of measurements required to support WE industry applications such as forecasting, which will always require a mix of measurements and modeling for accurate predictions.

**CONCLUSIONS.** In an industry so dependent on a variable resource, such as the wind, it makes sense to understand as much as possible about that resource. But this is not the case for wind: characterizing and understanding the resource is a serious gap for WE applications, which can be traced to a need for high-quality measurements through the atmospheric layer occupied by turbine rotors. The primary role for WE meteorology is to provide an acceptably accurate estimate of the inflow wind profile and other inflow properties, such as turbulence and stability. To isolate sources of error, for example, the first step is to address the question of how much of the uncertainty is due to errors in the unimpeded inflow estimate. Once this flow begins to interact with a wind turbine or wind farm, new sets of interactions come into play that are not strictly meteorological, such as turbine-wake effects, number of offline turbines, power demand, etc., which compound the uncertainties in predicted power output. If errors are evaluated after interaction with the turbines or a wind farm, then it is no longer possible to attribute inflow-related error and to sort out the other sources of uncertainty.

In a recent workshop the convener posed the question, what would it take to reduce the error in
the hour-ahead and day-ahead forecasts by 40%? Demonstrating at least this level of improvement will most likely be necessary to entice investment in advanced measurement arrays. Such improvement for the hour-ahead forecast is achievable by improved measurements, in the form of arrays of high-quality profile measurement sites. Improvement in the day-ahead forecast will require significantly improved NWP forecast models. It is perhaps ironic that the same kinds of instrument arrays needed for the hour-ahead forecast will also yield the kinds of datasets needed to significantly improve NWP skill, as well as providing the necessary advances to the state of the art in BL meteorology.

Reviews of essential WE industry needs from meteorology (e.g., Schreck et al. 2008; Shaw et al. 2009) imply that potentially huge amounts of revenue are forfeited each year because of inadequate meteorological information across the spectrum of WE industry applications. It is also conceivable that the WE industry’s future as a major component of the energy portfolio may depend on solving turbine maintenance issues related to the intensity and frequency content of turbulence encountered in the real atmosphere, on providing much more accurate forecasts at all time scales, especially the hour-ahead and day-ahead lead times, and other meteorology-dependent issues. Determining the value added of high-quality measurement systems and how they can be optimally integrated into forecasting and other aspects of the wind energy “process” is a worthy objective for future research projects, with the goal of demonstrating that investment in such systems is both wise and very cost effective. A positive and dramatic demonstration of such advantages, which is very possible, would motivate and justify expenditure on such systems by appropriate industry or governmental agencies.

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