Profiles of Wind and Turbulence in the Coastal Atmospheric Boundary Layer of Lake Erie

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Abstract. Prediction of wind resource in coastal zones is difficult due to the complexity of flow in the coastal atmospheric boundary layer (CABL). A three week campaign was conducted over Lake Erie in May 2013 to investigate wind characteristics and improve model parameterizations in the CABL. Vertical profiles of wind speed up to 200 m were measured onshore and offshore by lidar wind profilers, and horizontal gradients of wind speed by a 3-D scanning lidar. Turbulence data were collected from sonic anemometers deployed onshore and offshore. Numerical simulations were conducted with the Weather Research Forecasting (WRF) model with 2 nested domains down to a resolution of 1-km over the lake. Initial data analyses presented in this paper investigate complex flow patterns across the coast. Acceleration was observed up to 200 m above the surface for flow coming from the land to the water. However, by 7 km off the coast the wind field had not yet reached equilibrium with the new surface (water) conditions. The surface turbulence parameters over the water derived from the sonic data could not predict wind profiles observed by the ZephIR lidar located offshore. Horizontal wind speed gradients near the coast show the influence of atmospheric stability on flow dynamics. Wind profiles retrieved from the 3-D scanning lidar show evidence of nocturnal low level jets (LLJs). The WRF model was able to capture the occurrence of LLJ events, but its performance varied in predicting their intensity, duration, and the location of the jet core.

1. Introduction

The majority of offshore wind turbines are deployed within a few kilometers of the coastline and thus are located in the coastal zone [1], where the discontinuity in surface conditions induces non-stationarity, horizontal gradients of wind speeds and the development of internal boundary layers [2]. The understanding of wind characteristics relevant to the wind energy industry in these environments is hindered by the lack of detailed observations. For example, due to the difficulty and expense of operating meteorological towers offshore [3], long-term wind resource assessment typically relies on numerical weather prediction (NWP) models [4], and offshore wind turbine design employs the same external wind condition models developed for onshore wind turbines [5].

Flow within the lowest 200 m of the coastal atmospheric boundary layer (CABL) is rendered complex by a range of processes including: the surface inhomogeneity, the presence of swells that can result in upward momentum fluxes [6], the occurrence of land/sea breezes and strong moisture fluxes that can affect atmospheric stability and turbulent mixing in the CABL [7]. When these features are present, the Monin-Obukhov (MO) similarity theory, which is the theoretical basis for the surface layer parameterizations of NWP models, is not applicable. To understand how these specific processes affect the accuracy of NWP models in the CABL and to develop parameterization schemes that represent these
processes in NWP models, further offshore observations are necessary. The objective of the research presented herein is thus to use detailed measurements in the CABL (from a measurement campaign in Lake Erie from May 8 to 25 in 2013) to diagnose causes of non-ideal profiles of wind and turbulence and to evaluate the performance of the Weather Research and Forecasting (WRF) model in simulating the observed conditions.

2. Experiment Set-up
The purpose of this experiment is to investigate multi-scale wind characteristics in the CABL in a 3-dimensional space that has a similar size to an offshore wind farm. Multiple instruments were deployed in a triangular prism extending 7 km from the coast to the lake (from Port to Crib and Crib to Yacht Club as shown in Figure 1) as described below:

- ZephIR wind lidars (profilers) were installed at all three sites and operated to measure wind velocity and turbulence intensity at 40 m, 80 m, 120 m, 160 m and 200 m above the ground.
- A Galion G4000 scanning lidar was deployed on the port, conducting a combination of Plan Position Indicator (PPI) scans and Velocity Azimuth Display (VAD) scans with 68 range gates and range gate size of 30 m. For each cycle, the lidar started with a PPI scan from azimuth angle ($\theta$) 233º to 323 º with azimuth interval ($\Delta \theta$) 3º at elevation angle ($\phi$) 2º, and continuing the same PPI scans at

| Site     | Instrumentation                                      |
|----------|------------------------------------------------------|
| Port     | ZephIR (Unit# 128), Galion G4000, Sonic anemometer  |
| Crib     | ZephIR (Unit# 160), Sonic anemometer                 |
| Yacht    | Zephir (Unit# 127)                                   |

**Figure 1.** Overview of the instrument deployment. The thick dark line is the coastline of Lake Erie. The gray arc denotes the area scanned by the Galion Lidar. The inset map shows the innermost domain for the WRF simulation and the filled contours denote surface elevation in the domain drawn with a 60 m interval. The origin of the map corresponds to the center of the domain.

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\( \phi = [4, 6, 8, 10, 20] \, ^\circ \). It took about 10 minutes to finish the PPI scans from \( \phi = 2 \) to 10. As a result, the 5-stack PPI scans measured radial velocities in a partial sphere with radius \( \approx 2 \, \text{km} \) and can be used to investigate spatial variation of 10-minute mean wind velocity. The PPI scans were then followed by five VAD scans with \( \phi = 56 \, ^\circ \) and \( \Delta \theta = 30 \, ^\circ \). Measurements from VAD scans are used to estimate vertical profiles of mean wind speeds (over 4 minutes) with a height resolution of 25 m.

- **METEK and Gill Windmaster Pro 3-D sonic anemometers** were deployed on the port and the crib and operated using a sampling frequency of 10 Hz. Surface friction velocity \( (u^\ast) \), momentum flux \( (u'w') \), heat flux \( (\theta'w') \) and the Obukhov length \( (L) \) were derived for every hour.

The numerical simulations presented herein for the experiment period were conducted using the Weather Research Forecasting (WRF) system [8]. The WRF simulation was run with three domains using two-way nesting and 69 vertical levels. The innermost domain is centered at the port (Figure 1), and has 327×327 grid points at 1-km resolution. Seven heights are configured below 1000 m (30, 100, 197, 320, 475, 674, 916 m) above the surface at the port. Initial conditions and boundary conditions are prescribed from the North American Model (NAM) analysis data with 12 km resolution. The simulation presented in this paper was run with the MYJ PBL scheme and constant sea surface temperature. Wind speed data reported herein were stored every 10 minutes.

### 3. Results

The results described in this section focus on specific causes of flow modification and on evaluating the performance of WRF in simulating the flow relative to the observations.

#### 3.1. Land to Lake Flow

During the experiment, flow from the land to the lake (wind direction = 120-180\(^\circ\)) occurred most frequently at night and in the early morning. During these cases, the heat flux was typically negative at the port and positive at the crib as the air changes from being warmer than the land surface to cooler than the water surface. Data from the 3 ZephIR lidars indicate substantial acceleration of the flow as it moved offshore (seen by the positive values of gray box plots in Figure 2). The acceleration decreased with height, presenting a maximum value at 40 m height of \( \approx 1.5 \, \text{m} \, \text{s}^{-1} \) on average (Figure 2). The acceleration at all heights in the vertical profiles indicate that the internal boundary layer is higher than 200 m at the crib. However, at a distance of 7 km offshore, the winds had not yet reached equilibrium with the offshore conditions, which is consistent with previous research [9]. An example of this is given by the vertical profile of horizontal wind speeds measured on and off-shore during the night of May 20. Wind speeds increased at all heights when the flow moved from the land to the lake, as seen by the offset between the red line (lake) and the blue and the black line (land) in Figure 3. The Obukhov length \( (L) \) was negative and \( |L| < 50 \, \text{m} \) at the crib indicating very unstable conditions offshore. However, the observed vertical profile of horizontal wind speeds exhibited a shape that indicates a stably stratified atmosphere, which existed at the port during that night \( (0 < L < 50 \, \text{m}) \). The adiabatic wind profile shown in Figure 3 was calculated from the \( u^\ast \) and \( L \) derived from the sonic data at the crib, based on the MO similarity theory [10]. It is, to some extent, in agreement with the observed wind speed (red line) at 40 m height, but deviates considerably from the observed values at higher levels.

#### 3.2. Lake to Land Flow

For flow coming from the lake to the land (wind direction = 330-360\(^\circ\)), 40-m wind speeds were lower at the two coastal sites than at the crib (Figure 2). The slowing down of the wind speed was observed at all levels when comparing the crib to the port. However, deceleration was not seen when comparing the crib to the yacht club, where there was no difference between the wind speeds at the two locations above 40 m. The difference of wind speed between the two onshore sites is within the error range of the instruments, but it may be caused by the surrounding topography or the local built environment. Skyscrapers downwind of the port may have a blockage effect on the flow coming from water to land.
Figure 2. Boxplots of the wind speed difference between ZephIR measurements at five heights. (a) the crib (unit 160) versus the port (unit 128) and (b) the crib (unit 160) and the yacht club (unit 128). The gray boxplots are for flows directed from the land to the lake (wind direction = 120-180°) and the filled red boxplots are for flows directed from the lake to the land (wind direction = 330-360°).

Figure 3. Vertical profiles of horizontal wind speeds averaged between May 20 at 18:00 and May 21 at 09:00 for the crib (Z160, red line), the yacht club (Z127, black dots) and the port (Z128, blue squares). The $L$ values were negative and $|L| < 50$ m at the crib during this period. The sonic profile at the crib (thick black line) is estimated using the Monin-Obukhov similarity theory [10] and the $u_*$ and $L$ derived from the sonic data on the crib. The shaded area and the horizontal lines denote the standard deviations for the sonic profile and the Z160 profile, respectively.

3.3. Horizontal Wind Speed Distribution

The horizontal distribution of wind speed offshore at 40 m height near the coast was retrieved from the PPI scans using the Velocity Volumetric Processing method with only the horizontal wind components [11]. To investigate flow acceleration due to the small surface roughness over the water, the wind speed is normalized by the reference wind speed at the port measured by the ZephIR lidar (unit 128). Two special cases are presented here in terms of the influence of atmospheric stability on winds coming from the land to the lake. For the first case (Figure 2a) the atmosphere was unstable both onshore ($L = -53$ m at the port) and offshore ($L = -3.4$ m at the crib), while for the second case (Figure 2b) the atmosphere changed from very stable onshore ($L = 2.5$ m at the port) to very unstable offshore ($L = -35$ m at the crib).

Overall, the wind speed accelerated by up to ~20% in both cases (light red in Figure 3), but deceleration by ~10% also existed over a small portion of the area investigated (light blue in Figure 3).
Both cases show a non-uniform spatial pattern. The second case presented larger horizontal gradients and higher acceleration than the first case.

**Figure 4.** Horizontal distribution of the offshore wind speed at 40 m height estimated from Galion PPI scans and normalized by the ZephIR lidar’s wind speed at 40 m height at the port for (a) 06:00 EST on May 14 and (b) 19:00 EST on May 20 (EST = UTC – 5). The reference wind speeds were 7.43 m s\(^{-1}\) for (a) and 6.75 m s\(^{-1}\) for (b). Contour lines have an interval of 0.1 and the thick dark lines denote the level 1.0. The gray areas to the bottom right denote land.

### 3.4. Low Level Jets

The wind speed profiles retrieved from the VAD scans of the Galion lidar deployed at the port frequently exhibited evidence of a low-level wind speed maximum, a phenomenon known as low level jet (LLJ). According to the vertical profiles of wind speeds retrieved from the VAD scans of the Galion lidar, LLJs formed around midnight, intensified within the following 4 to 6 hours, and disappeared around 10:00 the next morning. They were observed from May 17 to 22, 2013. This period was characterized by sunny conditions with light wind during which a land-sea breeze circulation could be anticipated to develop at night. The jet cores were located between 200 and 400 m above the ground. They had a magnitude of around 14 m s\(^{-1}\), which was about 4 m s\(^{-1}\) higher than the wind speed within 100 m of the jet cores in the vertical (see examples in Figure 5 and Figure 7).

The observed LLJs at night may be associated with inertial oscillations (IO) induced in the nocturnal boundary layer (NBL) by the Coriolis force [12]. Wind speed gradually accelerates and becomes supergeostrophic at the peak of the IO as a result of the reduction in surface friction brought on by the suppressed mixing in the statically stable NBL. The amplitude of the IO is equal to the deviation of wind speed at sunset from the equilibrium wind speed in the NBL [13]. The period of the IO is about 18 hours at the port given the latitude at the site is 41.5º. This is consistent with the time scale of the observed LLJs which reached their peak values in 4-6 hours and lasted for about 9 hours. The other possible cause for the observed LLJs at the port is the thermal wind [12]. For the example shown in Figure 5, the location of the lake and the east-west slope to the south of the lake (seen in Figure 1) induced a thermal contrast at night and resulted in a 340º thermal wind (this was seen from WRF results at 600 m above the ground but not shown here). Given the geostrophic wind direction was about 250º at 600 m above the ground (from the WRF simulation), the thermal wind could cause wind speed to decrease and wind direction to veer with height which is consistent with the increase in wind speed and wind veering with height shown in the data.
Figure 5. Comparison of time-height variation of wind speed at the port (a) retrieved from Galion VAD scans and (b) simulated by WRF for May 13 and 14 2013. Arrows are not scaled to the wind speed but rather represent wind direction.

Figure 6. Vertical profiles of horizontal wind speeds measured by VAD scans of the Galion lidar and ZephIR lidars at the port (z128) and the crib (z160), and simulated by WRF for (a) 2013-05-14 06:00 EST and (b) 2013-05-17 00:00 EST. The gray area denotes the range of VAD scan wind speed within one hour. Horizontal lines are error bars for the ZephIR wind profiles (standard deviation within one hour).

WRF was able to capture these LLJ events, but its performance in predicting their onset, duration and intensity varies from case to case. In the morning of May 14 EST (Figure 5), although WRF predicted the location of the LLJ (Figure 6), it significantly underestimated the intensity by 6 m s\(^{-1}\). Moreover, the LLJ from the WRF simulation formed later and was of shorter duration than the observed. On the contrary, the WRF simulation accurately predicted the LLJ in the morning of May 17 (Figure 6 and Figure 7). It captured the location and the duration of the LLJ and only slightly underestimated the intensity.
4. Summary and Future Work

This paper describes the preliminary findings from a field campaign in the Great Lakes in May 2013 that was designed to improve understanding of offshore wind characteristics. Data from lidar wind profilers show on average ~ 1 m s\(^{-1}\) increase in wind speed for flow coming from the land to the lake over a 7-km fetch. When atmospheric stratification is stable onshore but unstable offshore, the vertical profile of wind speed over the water deviates from the adiabatic wind profile calculated from the Monin-Obukhov similarity theory. For flow coming from the lake to the land, wind speeds were similar on the coast and over the water. Low level jets were frequently observed at night and their occurrence may be linked to the inertial oscillation. WRF's performance in predicting these LLJs varies. For the two cases investigated in section 3, WRF was only able to capture the LLJ location in the first case, but in the second case it performed well in simulating the location, intensity and duration of the LLJ. Since the observed LLJs occurred in a height range (100 – 400 m above the ground) that is relevant to wind turbine operation, accurate prediction of these LLJs are important for wind energy applications. Further investigation of the cause of the discrepancies is needed.

Future work will also focus on changes in the vertical profile of wind speed offshore, particularly those associated with unstable conditions. The predictability of these wind profiles will be investigated using the high frequency lidar data and the sonic data as well as WRF simulation results. Swell data from the nearby buoy will be analyzed to investigate the effect of swell on wind profiles. The impact of atmospheric stability change across the coastline will also be investigated.

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