Characterizing marine atmospheric boundary layer to support offshore wind energy research

Houshuo Jiang*, James B. Edson**
Department of Applied Ocean Physics and Engineering
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

* hsjiang@whoi.edu, ** jedson@whoi.edu

Abstract. The marine atmospheric boundary layer (MABL), under most wind conditions, is characterized by lower shear, less turbulence, and higher winds than its terrestrial counterpart, thereby making offshore wind farms attractive enough to offset higher costs of construction and maintenance. Significant questions, however, remain about the structure and characteristics of the MABL and its impact on wind turbines. This work characterizes the structure of the MABL in the coastal region south of Martha’s Vineyard where offshore wind turbines are planned to operate, using in situ and remotely sensed LIDAR measurements and numerical data generated by high resolution Weather Research and Forecasting (WRF) modeling. This work will benefit wind power estimates and short-term energy forecasting.

1. MABL characterization

The Air-Sea Interaction Tower (ASIT) at WHOI’s Martha’s Vineyard Coastal Observatory (MVCO) provides an ideal platform to obtain in situ measurements of the velocity, temperature and humidity, and the associated fluxes of momentum, heat, and moisture. These measurements can be used with surface layer prediction of the velocity, temperature, and humidity profiles using techniques such as Monin-Obukhov Similarity Theory (MOST, e.g., Fairall et al. 1996). For example, the wind profile is predicted to take the form of:

\[ U(z) = U(z_0) + \frac{u_s}{\kappa} \left[ \ln \left( \frac{z}{z_0} \right) - \psi_m \left( \frac{z}{L} \right) \right] \]  

(1)

where \( U(z) \) is the wind speed at height \( z \), \( z_0 \) is the aerodynamic roughness length, \( u_s \) is a velocity scaling parameter known as the friction velocity, \( \kappa \) is von Kármán’s constant, and \( \psi_m \) is a function that accounts for stability effects where \( L \) is known as the MO length. The MO length represents the height at which the mechanical and buoyant production of turbulence are equal. This expression assumes a “constant” flux layer, which is typically assumed to be valid in the lowest 10% of the MABL.

MOST derived wind profiles are commonly used to extrapolate wind speeds measured near the ocean surface to the height of wind turbines (~100 m) to characterize the offshore wind field. However, the assumptions required to use MOST become invalid under strongly stratified and/or offshore airflows and in regions of significant horizontal inhomogeneity. Both of these conditions are commonly observed in coastal regions. To better understand this problem, the wind energy community has made significant
strides in the use of LIDARs (light imaging, detection, and ranging) to remotely measure offshore wind profiles from buoys and towers.

2. LIDAR measurements

We evaluate the performance of the LIDAR for measuring offshore wind profiles up to a height slightly above that of wind turbines. Funded by the MassCEC, a WINDCUBE® Vertical Profiling LIDAR has been operating since 2016 on the ASIT that is situated two miles south of Martha’s Vineyard in the outer continental shelf. Located in a fixed position on the ASIT platform, the WINDCUBE® LIDAR provides continuous measurements of the wind resource across the full vertical rotor span of wind turbines used in offshore wind farms. We also investigate the validity of Equation (1) using the LIDAR measurements under a wide variety of conditions. The parameters required for Equation (1) are derived using the COARE 3.5 algorithm (Edson et al. 2013) using in situ data collected on the ASIT and from the MVCO seanode.

The wind profiles measured by this LIDAR are compared with MOST predictions and with WRF numerical simulations. The MOST predictions under near neutral to convective conditions in onshore airflow agree best with the LIDAR measurements up to 100 m and beyond with enhanced winds aloft (Figure 1, left panel). This provides optimal conditions for application of MOST. The agreement degrades under stably stratified onshore airflow with frequently observed low-level jets (Figure 1, middle panel). The MOST predictions agree poorly with the LIDAR measurements in offshore airflow regardless of the stratifications (Figure 1, right panel).

Figure 1. Comparison of wind profiles measured by the LIDAR and predicted by MOST using ASIT measurements. The left panel shows results (wind speed averages over a 4 hour period) under convectively unstable conditions with onshore airflow, the middle shows results under stably stratified conditions for onshore airflow, while the right panel shows results in offshore airflow. The error bars and dashed lines represent the standard deviation about the mean shown by the symbols and solid line for the LIDAR and MOST, respectively, over a 4 hour period. The LIDAR and in situ data were made available by Dr. Anthony Kirincich and colleagues at WHOI.

3. WRF simulations

The New England Shelf offshore region is adjacent to a complex coastal land-sea-island setting and shallow water of a complex bathymetry. The region is often covered by a stably stratified MABL formed by warm air from land being advected over cold sea water; under this condition the MOST predictions are known to work poorly. The region also sits within the winter storm tracks that routinely impact the
Northeast along with occasional extreme winds from hurricanes. Therefore, there is a need to address the impact of high winds on turbine performance in severe weather.

Facing these complexities in geography, MABL structure, and synoptic weather conditions, we develop and implement a wind simulation framework based on the WRF model for MABL characterization and wind resource assessment for the New England Shelf offshore region. This simulation framework is called the Cape Cod Offshore WRF (CCO-WRF) that covers both the MVCO and the Offshore Wind Energy Federal Lease Areas offshore of Rhode Island and Massachusetts (Figure 2). Our WRF implementation includes two two-way nested domains: The inner domain of 1.5 km horizontal resolution, covering the region spanning from the MVCO to the Pioneer Array, is nested within a larger domain of 4.5 km horizontal resolution. The outer, larger domain is forced every six hours by the North American Mesoscale (NAM) model output as initial and lateral boundary conditions and uses the NCEP daily data of 0.083° global SST analysis (RTG_SST_HR; Thiébaux et al. 2003) as the bottom boundary condition. The WRF model is non-hydrostatic. An approach of consecutive integration with daily re-initialization (Jiang et al. 2009) is employed to run the CCO-WRF in a hindcast mode for individual days belonging to several typical MABL conditions measured at the MVCO/ASIT (Figure 3). The CCO-WRF output data is saved every ten minutes in model time.

We use a vertical grid resolution of ~2.5 m above the sea level for the lowest vertical grid point and 10 grid points within ~200 m above the sea level to resolve the vertical wind profile along the turbine height for the offshore environment. In total, we use 57 vertical levels with a top at 50 hPa. Even “high” resolution mesoscale models such as the WRF model have rather coarse resolution near the ocean surface. For example, almost all current applications of mesoscale atmospheric models for offshore wind assessment did not adjust the model vertical resolution and instead used the default vertical resolution settings, where the lowest vertical grid point is often above the wind turbine hub-height. Everything below this height is parameterized; e.g., Equation (1) is commonly used in numerical models to parameterize the velocity profile and surface stress using model values available at the first grid point above the surface. These parameterizations, however, become increasingly inaccurate away from the surface particularly in coastal regions with offshore or stratified airflows. Therefore, to be useful for this project, the model uses a very fine vertical resolution near the ocean surface.

Figure 2. Nested domains of the Cape Cod Offshore WRF (CCO-WRF). Domain 1: Parent domain with coarse grid resolution of 4.5 km; Domain 2: Covers the Cape Cod and islands and offshore, including the Offshore Wind Energy Federal Lease Areas offshore of Rhode Island and Massachusetts, the MVCO and the ASIT (marked by the two red stars), and the Pioneer Array, with fine grid resolution of 1.5 km.
Figure 3. A CCO-WRF simulated snapshot of the near surface conditions, i.e. sea level pressure, temperature at 2 m, and wind vectors at 10 m (only 15% of simulated vectors are shown), at 2017-04-19: 2100 UTC. This was a case of onshore airflow under an unstable condition at the MVCO ASIT site (marked by the red star).
We compare the CCO-WRF simulated wind profiles against the LIDAR measurements for three individual days belonging respectively to three typical MABL conditions identified at the MVCO ASIT site. For the day of 2017-04-19 UTC, a typical case of onshore airflow under an unstable condition (Figure 3), the CCO-WRF simulated wind profiles agree best with the LIDAR measurements up to 200 m and beyond with enhanced winds aloft (Figure 4a). This also corresponds to the optimal conditions where the MOST works best (Figure 1, left panel). For the day of 2017-07-20 UTC, a typical case of onshore airflow under a stably stratified condition where a low-level jet developed, the CCO-WRF simulated wind profiles display a low-level jet but compare poorly with the LIDAR measurements (Figure 4b). Figure 4c shows the results from the early morning of 2017-09-29 UTC, a typical case of offshore airflow under an unstable condition, the CCO-WRF simulated wind profiles compare reasonably well with the LIDAR measurements. The agreement actually improves over the course of the day as winds become more onshore. Note that the MOST predictions agree poorly with the LIDAR measurements for the latter two cases (Figure 1, middle and right panels).

Results from this preliminary investigation suggest that a WRF model of a high horizontal and vertical resolution can become a very promising tool to simulate the wind profiles from near the ocean surface to the height of wind turbines (~100 m) to characterize the offshore wind field. Often, it appears that the WRF model outperforms the MOST predictions in generating wind profiles that compare favorably with the LIDAR measurements. Nevertheless, CCO-WRF simulations for hundreds of individual days since 2016 are still needed to generate a large dataset to compare, in a statistical way, with the LIDAR measurements available for the same period of time. To improve the CCO-WRF’s skills in simulating cases of stably stratified conditions with low-level jet development, a SST product of a better quality will be used as the bottom boundary condition, and the standard WRF surface flux module needs to be replaced by a widely used air-sea flux bulk formula, i.e., the COARE 3.5 algorithm (Edson et al. 2013). These efforts will benefit the development of the WRF model into a reliable tool for offshore wind power assessment and short-term energy forecasting.

References

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