Scanning Doppler lidars for Wind Energy research and validation of NWP model wind forecast in complex terrain.

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Abstract.
Measurements from scanning Doppler lidars at three sites in the Columbia River Gorge during the second Wind Forecast Improvement Project (WFIP-2) are used to analyze the temporal and site-to-site variability of the wind profile, to better understand physical processes related to the terrain effects, weather conditions, and presence of wind farms. Continuous measurements from two 200S lidars for 18-months and year-long measurements from a StreamLine lidar provide a comprehensive dataset to validate NWP model wind forecasts and evaluate model accuracy over days, months and seasons, as well as for periods of interesting meteorological events including wind ramps, cold fronts, or marine push in the study area. Verification metrics such as bias, RMSE, MAE, and the correlation coefficient between observed and modeled wind variables are analyzed as a function of height, time, and forecast hour, revealing meteorological features that are not well represented by models and provide insight to potential model improvements.

Introduction.
The basin of the Columbia River in Oregon and Washington is the site of many large wind farms and a major source of wind energy to the Western U.S. The imposing Cascade Mountain Range provides a natural barrier between the Pacific marine air to the west and the arid conditions over the wind-farm study area to the east. Wind flow through the Columbia River Gorge, the only sea-level gap through this range. Typical weather patterns can be identified for summer and winter conditions over the Basin. During summer a persistent offshore subtropical ridge to the west of the range and very strong diurnal heating of the dry interior to the east, including the wind-farm region, drive a predominant westerly wind flow having a diurnal cycle that peaks at midnight local time. In winter, frequent storm and frontal systems, and resulting low surface pressure offshore combine with high pressure inland, often associated with multiday persistent cold-air pools and their strong inversions in the basin regions. This configuration produces a pressure gradient favoring easterly flow through the Columbia Gorge and cold air pool conditions over the Basin, including a very weak, mostly easterly but highly variable drift to the winds there.

Properties of winds at the hub-height and within the turbine rotor layer, their temporal variability for monthly, seasonal, and annual time scales as well as their spatial variability over the complex terrain of this large basin are important for wind industry operations.

In this study wind properties are measured using scanning, pulsed Doppler lidars sited along the Columbia River wind corridor at three sites along a distance of 70 km (Fig.1).

Lidar measurements provide wind speed and direction profiles every 15 min at high precision (<10 cm s⁻¹) and resolution (vertical spacing of ~10 m or less through the rotor layer). Consecutive measurements from all 3 lidar during a 12-month period in 2016 are used to quantify spatial and temporal wind variability at each site and between sites, and to validate numerical weather prediction (NWP) model winds in the lowest 1 km above ground level (AGL) and to obtain model-error metrics for any given height, time of day,
season or over particular layers of the atmosphere, focusing on the hub-height and the rotor-layer that are important to wind energy.

The model used for comparison was the NOAA/NCEP HRRR NWP operational forecast model as described by Benjamin et al. (2016).

The lidar deployments were part of a larger field campaign, the Second Wind Forecast Improvement Program, or WFIP-2, from September 2015 through March 2017. Overviews of the WFIP-2 experiment and scientific objectives, detailed description of instruments involved in the experiment as well as the logistics of their deployments, and the improvements of NOAA/ESRL and NOAA/NCEP operational models as well as better-resolution experimental models are in preparation as well as many other papers coming out of the analysis of this reach data set.

Figure 2. The top part shows Google map of the Eastern Gorge part of the study area shows the location of 2 NOAA Doppler lidars (200S) at Wasco site at 469 m above Ground level (AGL) and Arlington site at 179 m AGL and the Notre Dame University HALO lidar at Boardman site at 111 m AGL. The distance between two NOAA lidars along the white line is about 40 km, and between lidars at the Arlington and Boardman sites is about 31 km. The surrounding wind turbines are indicated by the clusters of dark yellow circles. The blue line indicates the East-West Transect of the study region along the prevalent wind directions observed from surface measurements and models during previous studies in this area. The bottom part shows terrain elevation along this line and lidar locations shown by blue stars.

Results.

To illustrate the nature of the data and model information being used, Fig. 2 shows lidar time-height cross sections for each of the three sites for two individual days: 26 February, a wintertime day, and 28 June, a summer day. Also shown are the corresponding HRRR model cross sections for the 1- and 3-h forecasts. The bottom rows show time-height cross sections of the model-minus-lidar wind-speed differences (model bias errors). The wind patterns on 26 February consisted of diminishing easterly gap flow due to a synoptic slackening of the pressure gradient across the Cascades, and the buildup of a weak-
wind, cold-air-pool layer. The model predicted the weak-wind layer at Arlington and Boardman, but at Wasco the stronger winds persisted, indicating that the top of the weak-wind layer was predicted to be below the elevation of Wasco during this period. The timing of the wind-down ramp and the vertical structure of the departing westerlies are major sources of model error through the lowest km. The wind-speed patterns on 28 June reflect the summertime diurnal cycle of winds due to daytime heating and nighttime cooling of the Basin.

Figure 3 shows the annually averaged model-verification statistics for wind speed within the rotor layer as a function of (a) forecast lead time and (b) diurnal cycle. RMSE values (Fig. 3a) were \( \sim 3 \text{ m s}^{-1} \) for the first 2 h at this height, modestly increasing with lead time to \( \sim 3.5, 3.1, \) and \( 3.1 \text{ m s}^{-1} \) at Wasco, Boardman, and Arlington, respectively. The winds at the lower two sites showed low biases of less than \( 0.5 \text{ m s}^{-1} \), the largest magnitudes occurring at 5 and 6 h lead time, but at Wasco, the speeds were biased high by approximately \( 1 \text{ m s}^{-1} \). Thus, annually averaged model forecast skill did not significantly degrade with lead time, out to 15 forecasts hours (Fig 3a), but show some diurnal variability (Fig. 3b). Similar analysis for monthly and seasonal averages show that larger positive errors of a hub-height winds at the Wasco site are mostly attributed by errors from the cold period months. The time-of-day variations of model error were not strong but did occur. For example, the summertime negative biases at Arlington and Boardman had the largest magnitudes at night, when the marine-intrusion/sea-breeze flows would be occurring at those sites. Another exception was that the R2 correlations were especially bad during the day at Wasco in fall, and to a lesser extent in winter. This behavior was consistent with daytime mix out in the model, reinforcing the premature mix out hypothesis at Wasco.
Conclusions:

Mean values of hub-height wind speed and direction can vary significantly over a wind plant, especially in terrain as complex as central Oregon and Washington. Measurements from three scanning lidars separated from each other by 30-40 km, over a total distance of 70 km, and sited at different terrain elevations provide an opportunity to characterize the winds at each site, to quantify the site-to-site wind-flow variability and to better understand physical processes related to the terrain effects, seasonality, or diurnal cycle and to capture cases of unusual wind flow such as wind speed and direction ramps, cold fronts, or marine pushes. High-resolution lidar measurements provide a comprehensive dataset to validate NWP model forecasts at each site and to obtain model-error metrics.

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