Atmospheric features as captured by scanning Doppler lidar and predicted by NWP modelling systems in complex terrain

Pichugina Y. (a, b), A. Brewer (b), C. Clack, Banta (b), A. Choukulkar, J. Olson, M. Marquis (b), J. Kenyon, S. Baidar, T. Bonin, A. Weickmann, S. Sandberg (b) and R. Hardesty

(a) Cooperative Institute for Research in Environmental Sciences, Boulder

(b) National Oceanic and Atmospheric Administration, Boulder

Abstract: The paper presents case studies of atmospheric features, captured by scanning Doppler lidar measurements during the Wind Forecast improvement Project-2 (WFIP-2) in the complex terrain of the Columbia River Valley. This 18-month long project, sponsored by DOE and NOAA, is aiming to improve forecasting of wind flow complicated by mountainous terrain, coastal effects, and the presence of numerous wind farms in this area. In addition to the analysis of the observed meteorological events, a high-precision Doppler lidar data are being used to validate the ability of National Weather Prediction (NWP) models to forecast wind flow at the heights of wind turbine rotors and above. Preliminary results on lidar-captured wind-flow features, along with examples of model validation by lidar data, are described

Keywords: Doppler pulsed lidar, wind forecasting, complex terrain

1. Introduction

Reducing the cost of wind energy and mitigating risks associated with wind plant operations require better forecasts of overall weather conditions and particularly wind flow variability at the heights of wind turbine rotors. To improve numerical weather prediction (NWP) forecasting of winds in complex terrain the Second Wind Forecast Improvement Project (WFIP-2) is taking place in the Columbia River Basin in the states of Oregon and Washington, USA. (Fig.1a). This 18-month research experiment uses the expertise of scientists and engineers from several universities, government laboratories, and private companies to investigate atmospheric phenomena that affect model accuracy in complex terrain and improve model physics using measurements from variety of conventional and remote-sensing instruments deployed to the study area.

2. Study area and lidar locations

The Google map of the study area located east of the Cascade Mountain Range is shown on Figure 1a. Several high-elevation mountains, the Columbia River canyon, and local terrain features as well as the presence of numerous wind farms create complex wind flows. Along with other instruments, two scanning pulsed Doppler lidars were deployed by NOAA/ESRL in September 2015 to two sites about 40 km apart (Figure 1b) to provide accurate, detailed wind profiles from the surface up through the boundary layer in real-time.

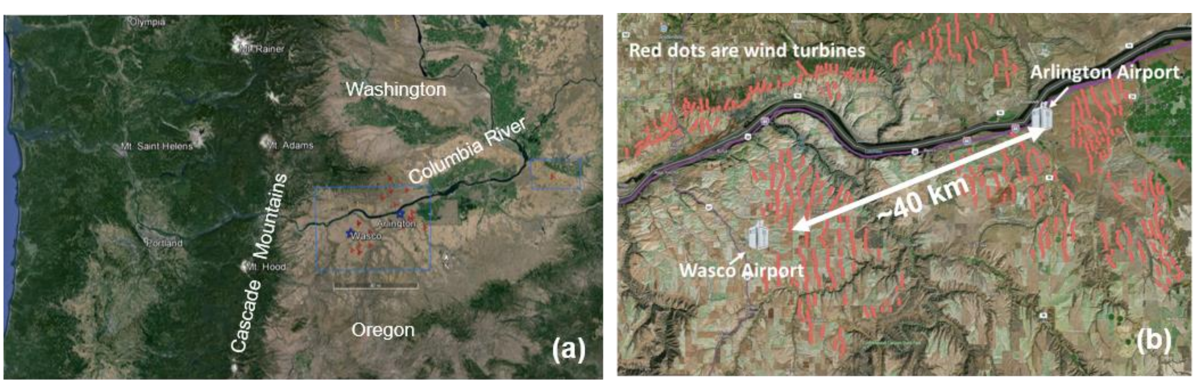

Figure 1. (a) Complex terrain of the Columbia River Basin. The WFIP 2 study areas showed by the blue rectangles. (b) Location of NOAA Doppler lidars (200S) at Wasco site at 469 m AGL and Arlington site at 179 m AGL. The surrounding wind turbines are indicated by the red symbols.

The lidar measurement routine includes a combination of multiple azimuthal scans, elevation scans, and vertical staring profiling, repeated every 15 min. Individual scan data, as well as computed, high vertical resolution profiles of wind speed, direction, and 3 wind vector components, provide critical information on wind flow variability (wakes, ramps, diurnal fluctuations), LLJs, rotor-layer shear, and turbulence. Some examples of wind flow features observed from lidar measurements are shown in the next section.

3. Capturing wind flow events

4.1 Wind turbine wakes

Deployment of two identical lidars to separate sites allows diurnal wind flow variability to be monitored at each site and between sites as illustrated in Figure 2a. The western lidar at Wasco documents an inflow profile upstream of the wind farms, whereas the eastern lidar at Arlington shows how flow changes due to distance and how wind farms affect the shape and magnitude of the wind profile, when the flow is from a westerly direction. Measurements obtained upstream and downstream of the local wind farms provide an opportunity to study turbine wake effects. An example of wakes downwind of the turbine array is shown in Figure 2b. West-south-westerly winds in the rotor layer at the Wasco site (Fig. 2a) create wakes downwind of a line of turbines, as observed by lidar at the Arlington site on October 1, 2015 during azimuthal (conical) scanning at 2.5^0 elevation angle. Velocity reductions of 3-4 ms^{-1} were detected up to ~1 km downstream of wind turbines for several hours through this day.

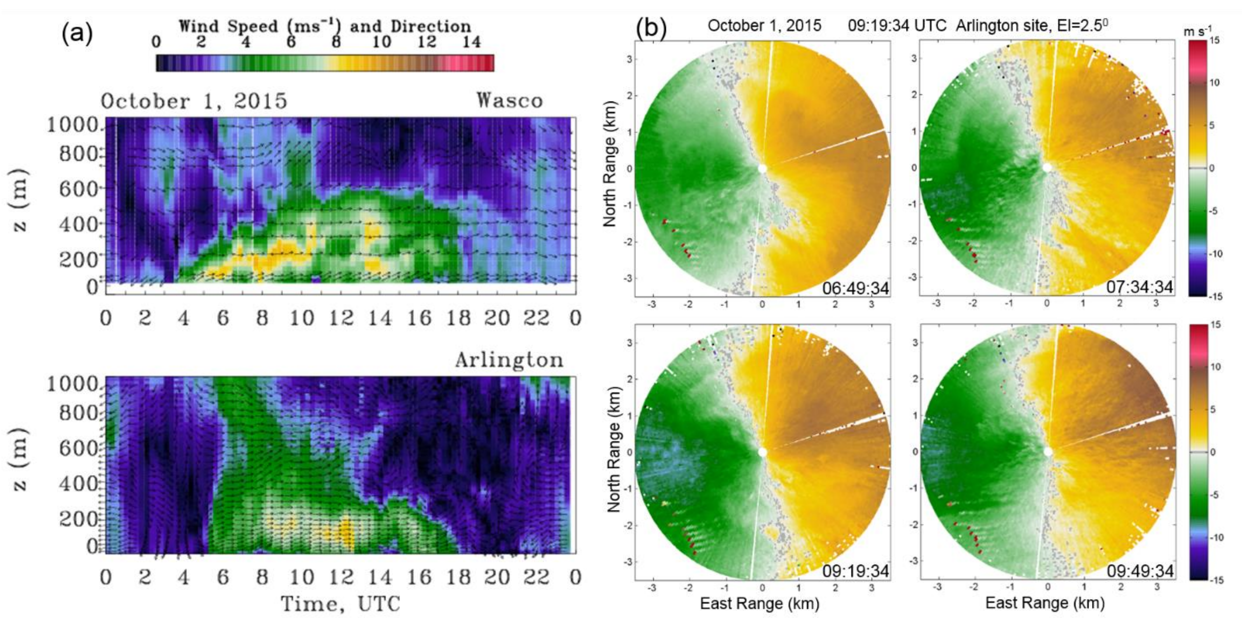

Figure 2 (a) Time height cross sections of wind speed and direction from lidar measurements at 2 sites. Wind speed is color coded from 0 to 15 m/s, black arrows show wind direction. (b) Conical azimuth scan at 2.5 elevation at the Arlington site shows a mean westerly flow over the scan disk. Several parallel streaks, representing wind turbine wakes can be seen in the southwest sector of each scan.

4.1 Wind ramps

Sudden changes in wind speed or wind direction (ramps) cause rapid changes in the power generated by the wind turbines and thus influence overall energy production. An example of an observed wind ramp event during May 7-10 at both sites is shown in Figure 3. On May 7 NE winds in the rotor layer were light at both sites. From May 8 through early morning on May 9 westerly winds increased up to ~20 ms^{-1}, as a strong

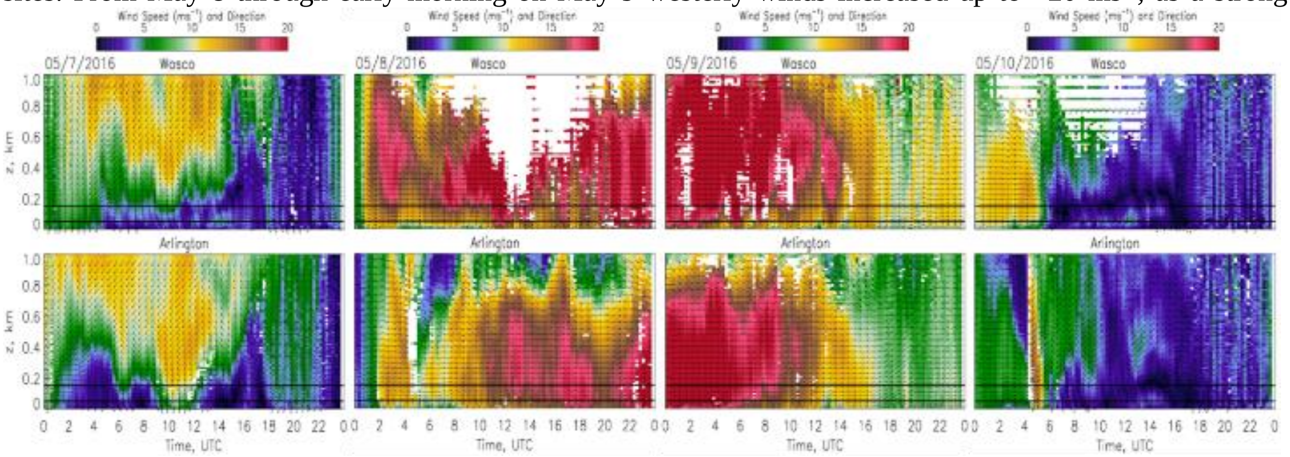

Figure 3. Time-height cross sections from lidar measurements during observed wind speed ramp event during May 7-10. Wind speed is scaled from 0 to 20 m/s. Two black horizontal lines indicate heights of the rotor layer (50-150 m).

offshore ridge pushed onto the coast. Then wind speeds abruptly decreased to 4-5 ms^{-1} during May 10, changing direction to NE. During this period the huge ramp in power production was reported by the BPA balancing authority. Note that winds at any given time at the Wasco site, compared to the Arlington site, indicate wind flow variations due to the distance, different elevations of the lidars, and the presence of wind turbines. This is an important issue for selecting a proper site for any measurement system. In addition to monitoring variability of winds, lidar data along with data from other instruments, model output, and satellite images are being used to assess meteorological conditions that may affect the accuracy of model forecasts as well as WE operations.

5 Model validation

In contrast to other instruments, lidar data are not assimilated into models, providing "independent" datasets for model verification and improvement. During WFIP 2 the high-precision Doppler lidar data are being used in real-time to validate the ability of NWP models to predict wind flow in the rotor layer and above (http://www.esrl.noaa.gov/csd/groups/csd3/measurements/wfip2/), and for post-processing analyses. Several models were validated and their domains are shown in Figure 4a.

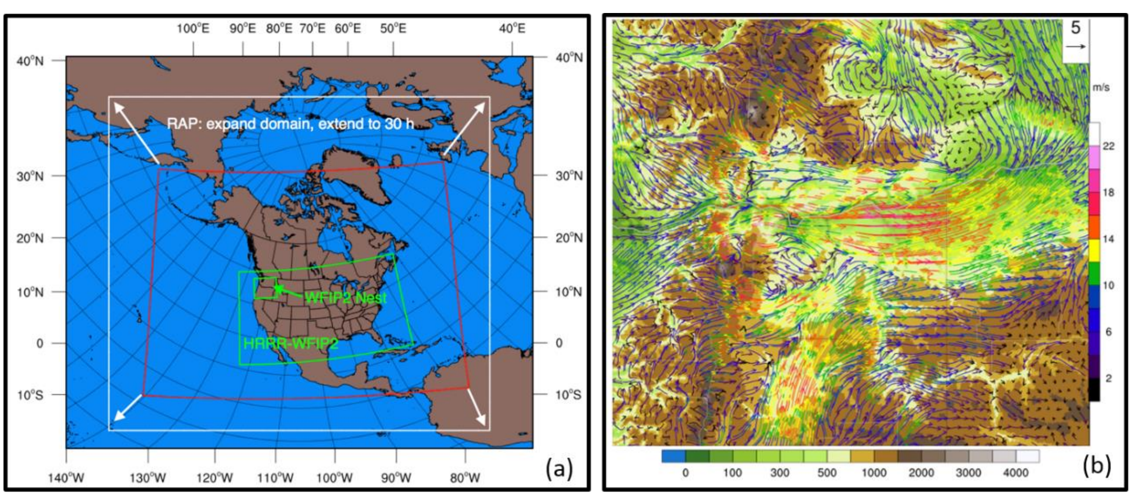

Figure 4. (a) Domains of WFIP 2 models. (b) Modeled wind flow at 80 m superimposed on area topography. (Both plots are courtesy of the NOAA Global Monitoring Division)

This paper will focus on the nested version of the High Resolution Rapid Refresh (HRRR-nest) model developed at ESRL for the WFIP2 experiment. The horizontal grid of this model is 750 m and outputs produced at 50 vertical levels. Forecasts are produced for 18 lead times. Modeled 80-m winds over HRRR-nest domain are shown in Figure 4b to illustrate the complexity of wind flow in the research area.

An example of measured and predicted wind flow at each site is illustrated in Figure 5a. Model captured major trends of wind speed and direction relatively well, but timing of wind ramps is not accurate. Details of rotor layer wind speed comparison statistics for this day are shown in Figure 5b

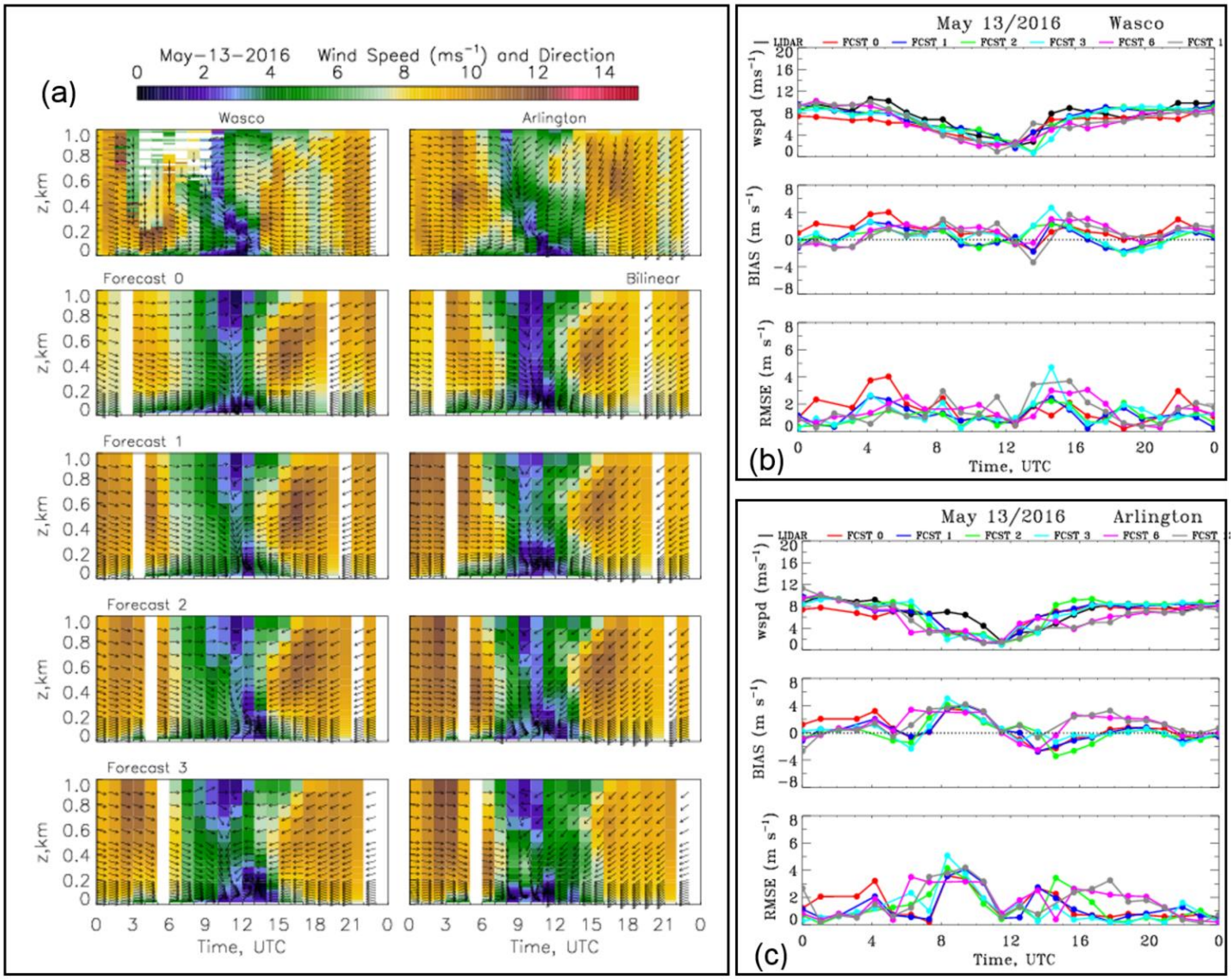

Figure 5. (a) Measured (top panels) and predicted wind flow for forecast hours 0-3 on May 13, 2016 are shown for (left panels) Wasco and (right panels) Arlington sites. (b) Time-series of the rotor-layer mean statistics between measured and modeled wind speed at (top) Wasco and (bottom) Arlington sites.

5 Conclusions

NOAA Doppler scanning lidars, along with other observing systems, provide comprehensive datasets to characterize complex terrain atmospheric phenomena that impact model accuracy, and to validate and improve model physics and wind forecasts.