THE SECOND WIND FORECAST IMPROVEMENT PROJECT (WFIP2)

General Overview

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WFIP2, a multi-institutional, multiscale modeling and observational study in complex terrain, advances understanding of boundary layer physics and improves forecasts for wind energy applications.

At the end of 2017, installed energy generation capacity from wind in the United States exceeded 87 GW, and wind energy is expected to exceed hydropower as the nation's largest renewable energy source in 2019 [U.S. Department of Energy (DOE); DOE 2018a]. Wind power plants now provide more than 6% of U.S. electrical power production (DOE 2018b). With the cost of wind energy falling rapidly, that percentage is projected to increase to 20% by 2030 and 35% by 2050 (DOE 2015). At the same time, wind is a variable energy resource, and as wind's percentage of the U.S. energy mix increases, so will the importance of accurately forecasting it in order to efficiently operate electric systems and related markets and to ensure grid reliability (Marquis et al. 2011).

Weather forecasting for wind energy suffers from several challenges. First, there has been limited validation of wind forecasts at 100 m above Earth's surface (approximately wind turbine hub height) owing to the general lack of observations at that height. Another is that the same lack of observations inhibits initialization accuracy for forecast models. A further, and perhaps most significant, challenge is that wind power plants are frequently placed in complex terrain, creating more severe demands for model physics. Renewable energy industry experts, university researchers, and federal scientists have met regularly over the last decade to address the challenges of transitioning the power grid from conventional energy sources to renewable sources. In addition to the energy conferences at the AMS Annual Meeting and the Energy Systems Integration Group (formerly called the Utility Variable-Generation Integration Group) annual forecasting meeting, DOE has held two key workshops to identify research priorities to reduce the cost of wind power. A DOE workshop in 2008 titled "Research Needs for Wind Resource Characterization" (Schreck et al. 2008; Shaw et al. 2009) and another in 2012 titled "Complex Flow" (DOE 2012) documented the need for atmospheric science advances across a range of scales: turbine scale, wind plant scale, mesoscale, and global scale. Both workshops determined the need for field campaigns to collect observations for model validation and

A2E INITIATIVE

WFIP2 is a study within the Atmosphere to Electrons (A2e) initiative begun by DOE's Wind Energy Technologies Office in 2015. The overall objective of A2e is to optimize the power production of wind plants as a whole rather than by individual turbine. Such optimization requires improved and detailed knowledge of boundary layer winds and turbulence and of wind turbine and plantwide aerodynamics as well as the development of control systems that account for these processes across the wind plant. The three disciplines—the atmospheric boundary layer, aerodynamics, and system controls—represent three intellectual communities that typically engage each other tangentially. Closer communication and coordination among these communities through A2e facilitates problem solving where their disciplines intersect. For example, wind plants are commonly sited in complex terrain, where thermodynamic stability varies strongly over the diurnal cycle. In addition, the wind field can vary strongly over the $O(10)$-km horizontal dimension of a wind plant. However, partly for computational expediency and partly from incomplete understanding of the behavior of the atmosphere, aerodynamicists have often used simplified inflow conditions such as neutral stability and a simple logarithmic wind profile to drive simulations of the production and impact of wakes generated by upstream turbines on those operating downstream. Conversely, atmospheric scientists have in many cases addressed problems assumed to be important for wind energy without engaging aerodynamicists directly to understand what is useful and usable. Thus, two motivations drove the development of the A2e initiative: to address the complex, interdisciplinary problem of wind plant optimization and to provide a structure in which information would be shared efficiently among disciplines.

The A2e initiative reflects an explicit partnership between DOE and its national laboratories as well as strong collaboration with other federal agencies and the academic community. To oversee the program, DOE developed an Executive Management Committee comprising federal program managers and subject matter experts from the national laboratories leading atmospheric sciences, aerodynamics, and controls work. The intention of this structure was to assure interdisciplinary integration within overall DOE priorities. Specific focus areas within A2e include the following:

- High-fidelity modeling, verification, and validation: encompassing mesoscale and large-eddy simulation (LES) modeling of the atmosphere, turbine-resolving modeling of wind plants, and field studies to improve and validate the models. High-performance computing enables detailed simulation of complex flows.
- Integrated wind plant control: developing new technology in which controllers for individual turbines act with awareness of all other turbines enabling, for example, steering of wakes away from downstream turbines to maximize power production and minimize turbulent loads.
- Integrated system design and analysis (ISDA): Developing tools to incorporate new knowledge gained through A2e to optimize and assess the design and performance of wind plants.
- Reliability: assessing impacts on turbine and plant lifetimes resulting from new modes of plant operations.
- Performance, risk, uncertainty, and finance (PRUF): assessing the financial impact of reducing uncertainties in wind plant power production from improvements in each of the above focus areas, providing a way to prioritize research resources.
- Data archive and portal (DAP): providing an enduring archive for public use of field data collected and benchmark model output generated under the A2e initiative.

development, advanced supercomputing, data sharing and archiving, and a high level of coordination.

An earlier study in 2011/12, known as the Wind Forecast Improvement Project (WFIP1; Wilczak et al. 2015) focused on the initialization problem by examining the impact that assimilating enhanced observations has on forecast accuracy. Results demonstrated that assimilation of the combination of the special WFIP1 remote sensing and industry-provided tall tower and turbine nacelle anemometer observations provided a 3% reduction in root-mean-square error (rmse) for wind power forecasts averaged over the first six forecast hours (Wilczak et al. 2015). A larger reduction of 6% rmse over this same forecast horizon was found for the regionally aggregated wind power production, which may be of more relevance for balancing the electric grid. A follow-on study (Wilczak et al. 2019a) demonstrated that assimilation of the more numerous tall tower/nacelle observations alone provided a relatively large improvement through the first 3–4 h of the forecasts, which diminished to a negligible impact by forecast hour 6. In comparison, assimilation of the sparser vertical profiling remote sensors alone provided an initially smaller impact that decayed at a much slower rate, with a positive impact present through the first 12 h of the forecast. Assimilation of the WFIP1 special observations also was shown to significantly improve forecasts of wind ramp events (Bianco et al. 2016; Akish et al. 2019), which are of great importance for balancing the grid.

In 2015, DOE initiated a 4-yr study, the Second Wind Forecast Improvement Project (WFIP2), to improve the representation of boundary layer physics and related processes in mesoscale models for better wind and wind power forecasts in complex terrain. WFIP2 was an interagency, public–private partnership under the Atmosphere to Electrons (A2e) initiative (see the "A2e initiative" sidebar) comprising DOE and National Oceanographic and Atmospheric Administration (NOAA) laboratories as well as the wind industry and academia through a team led by Vaisala, Inc. The Vaisala team proposed the Columbia basin as the focus area for the study in their winning response to a DOE funding opportunity announcement. The rationale for this kind of partnership was not only to carry out basic atmospheric research but also to provide a path for incorporation of improvements into both NOAA's foundational operational forecasts and the forecast services provided by industry. Primary participants are listed in Table 1 together with external collaborators who provided significant data or other assistance to the project.

Table 1. Participating organizations in and external data contributors to WFIP2.

Participating entity	Organization
Vaisala, Inc.	National Center for Atmospheric Research Notre Dame University Texas Tech University Sharply Focused, LLC University of Colorado Boulder Vaisala
U.S. Department of Energy	Argonne National Laboratory Lawrence Livermore National Laboratory National Renewable Energy Laboratory Pacific Northwest National Laboratory
National Oceanographic and Atmospheric Administration	Air Resources Laboratory Earth System Research Laboratory National Centers for Environmental Prediction
External data contributors	Avangrid Bonneville Power Administration Eurus Energy National Weather Service NextEra Energy Portland General Electric Siemens Heavy Industries Southern California Edison Company White Creek Wind

WFIP2 comprised three distinct but integrated components: a multiscale field study spanning 18 months, a model development effort, and the development of support tools to assist the industry in wind power forecasting. Each of these components will be fully described in its own overview paper in this journal. The overview of observations (Wilczak et al. 2019b) appears in the current issue. Overviews of model (Olson et al. 2019) and decision support tool (Grimit et al. 2019, in preparation for *Bull. Amer. Meteor. Soc.*) developments will appear in subsequent issues. A related effort to refine methods for coupling mesoscale and microscale models for wind energy applications is using observations collected during WFIP2. An overview by Haupt et al. (2019) will also soon appear in this journal. The purpose of this article is to provide a general overview of the scope and motivation of WFIP2 and to highlight some of its key outcomes.

ATMOSPHERIC CHALLENGES IN COMPLEX TERRAIN. The challenge of complex-terrain meteorology has attracted attention for decades. Among the earliest concerted efforts to gain insight into these flows was DOE's Atmospheric Studies in

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Complex Terrain (ASCOT) program, which included a series of field studies that extended from the late 1970s to the early 1990s (Orgill and Schreck 1985; Clements et al. 1989; Coulter and Martin 1996). As measurements and computational capabilities advanced, so did the comprehensiveness and sophistication of the approach to complex-terrain studies. The Mesoscale Alpine Programme (MAP; Bougeault et al. 2001) in 1999 was a large international effort to better understand and simulate the impact of orography on precipitation and hydrology, and its focus included boundary layer behavior in steep terrain. The Vertical Transport and Mixing (VTMX) study in 2000 combined modeling and meteorological observations with tracer measurements to reveal the behavior of circulations in the Salt Lake Valley and the ability of mesoscale models to replicate them (Doran et al. 2002). Another significant effort, which focused particularly on improving weather prediction in complex terrain, was the 5-yr Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) program that began in 2011 (Fernando et al. 2015; Di Sabatino 2016). Most recently, and with a focus specifically on wind energy, the New European Wind Atlas (NEWA) project (Mann et al. 2018) has carried out a series of field studies of increasing complexity to provide validation data for models that will be used to provide a more accurate wind atlas for Europe and Turkey. The studies culminated in a comprehensive measurement effort involving multiple remote sensing systems, numerous surface flux towers, and a multitude of other measurements to capture the winds and turbulence across two parallel ridges and the valley between near Perdigão, Portugal, during May–June 2017 (Fernando et al. 2017; Wildmann et al. 2018).

Physical phenomena associated with complex terrain include slope flows, mountain–valley/plain circulations, gap flows, topographic wakes, cold pools, and gravity waves. These phenomena are driven by a combination of dynamic or thermodynamic forcing and modulated locally by the terrain and by variations in land cover, surface moisture, slope shading by terrain, and clouds. The result is complicated atmospheric flow that is nonstationary and inhomogeneous over a broad range of scales. Serafin et al. (2018) have recently provided a comprehensive review of key challenges to understanding and simulating boundary layer exchange processes in complex terrain. These challenges include strong horizontal forcing that makes horizontal gradients of turbulent fluxes potentially as important as vertical exchange, which is generally not accounted for in parameterizations, (e.g., Rai et al. 2017). Further, conventional assumptions underlying many subgrid-scale parameterizations, such as horizontal homogeneity, stationarity, and constant flux layers at the surface need to be reexamined. Lehner and Rotach (2018) noted a number of challenges to numerical weather prediction modeling in complex terrain, including the representation of soil and land cover; the appropriate parameterization of shortwave and longwave radiation; the need for finer grid resolution in increasingly steep terrain; the associated "terra incognita" (Wyngaard 2004), where model resolution approaches dominant turbulence length scales; and numerical issues that arise with terrain-following coordinates when terrain becomes steep (e.g., Mirocha and Lundquist 2017; Arthur et al. 2018).

An additional challenge in complex terrain populated by wind turbines is accounting for the impact the turbines have in addition to the natural landscape on atmospheric flow. The WFIP2 domain includes over 6 GW of installed wind capacity, and wind forecasting models must consider possible effects of those turbines on local microclimates as well as the general wind behavior. Wind farms can warm the local environment at night by approximately 0.5°C by mixing warmer air aloft down to the surface (Baidya Roy and Traiteur 2010; Zhou et al. 2012; Rajewski et al. 2013, 2014; Smith et al. 2013; Armstrong et al. 2016). Large wind farms also create wakes, or regions of reduced wind speed, downwind, that can undermine power production at downwind wind farms (Nygaard 2014; Lundquist et al. 2018). Wind farms' effects can be incorporated in mesoscale models (Fitch et al. 2012, 2013; Volker et al. 2015); these effects have been validated offshore (Jiménez et al. 2015; Siedersleben et al. 2018) and in flat terrain (Lee and Lundquist 2017) but not yet in complex terrain.

WFIP2 APPROACH. Serafin et al. (2018) noted that progress in understanding complex-terrain meteorology requires dense measurement networks, including remote sensing, that can map the state of the atmosphere. Further, high-resolution numerical weather prediction models with appropriate numerical methods and parameterizations are required to represent the essential flow characteristics resulting from the atmosphere's interaction with the terrain. Combining observations with detailed modeling was the central strategy for WFIP2 with the following key elements:

- Observing boundary layer structure on multiple scales over a full annual cycle

DATA ARCHIVE AND PORTAL: MAKING DATA ACCESSIBLE TO THE PUBLIC

The DAP, a key component of the A2e initiative, was developed to make relevant historical data as well as new data, both field measurements and model benchmark runs, readily available and easily accessible and to facilitate their use by the research community. The scope of the DAP is to provide a secure, enduring archive to enable access to all significant wind energy–related data collected by projects such as WFIP2 supported under A2e. The archive supports unrestricted access to open data as well as restricted access to proprietary data through multifactor authentication. Users can access open data by registering for an account online (https://a2e.energy.gov/about/dap).

The DAP is an integral part of WFIP2. As part of ingesting and disseminating data provided via streaming or manual uploads by WFIP2 instrument providers and modelers, the DAP team provided file naming standards, coordinated user access, and assisted users in preparing data for upload. The naming convention includes indicators within the individual file names that denote the state of data within the file: "raw," "quality controlled," and "processed." A key part of the archival process is capturing metadata for all instruments and archived model output, which was required of data providers and accomplished through the web portal. The DAP uses a data ingest framework that is capable of running in a cloud-computing environment and can implement stateless ingest processes. The stateless ingest process allows concurrent processing of many files by distributing the workload across compute nodes in the cloud environment with no dependencies on input files.

In addition to archiving data, the DAP also provides visualization capability. It would not have been efficient to manually review data from the many thousands of files produced during the WFIP2 field study. The visualization tool enables quick selection of relevant fields and time periods from instruments of interest and includes an animation capability. These visualizations were critical in particular to the development of the WFIP2 event log, which was the basis for the selection of case studies. An example visualization is shown in Fig. SB1. In addition to visualizations from WFIP2 instruments, the DAP also acquired satellite and analysis images via the University of Washington during the period of the field study. In all, more than 2 million data files and photographic images are stored within the DAP as part of WFIP2. As of mid-December 2018, WFIP2 had 277 datasets with 18 million files totaling 210 TB stored on the A2e DAP (to browse WFIP2 data directly, please to go to https://a2e.energy.gov/projects/wfip2).

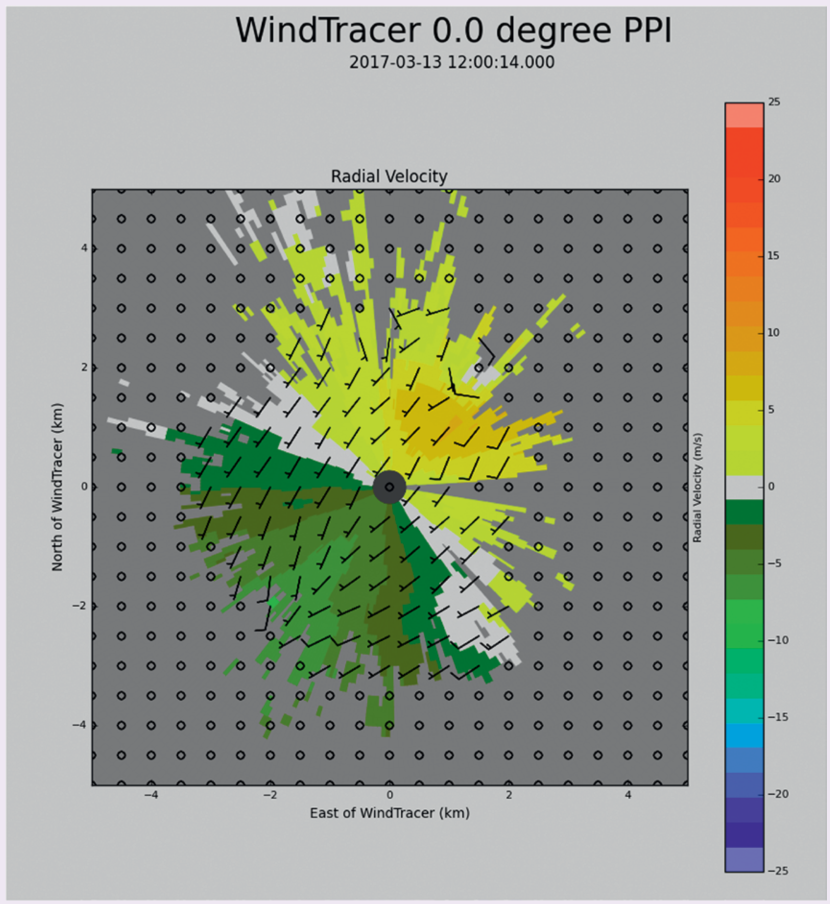

Fig. SB1. Visualization by the DAP of radial velocity with derived wind barbs from the WindTracer lidar deployed during WFIP2.

- Using the data collected to evaluate baseline NWP model performance as well as improvements in parameterizations and numerical techniques over the spectrum of atmospheric conditions in an annual cycle
- Using observations to establish uncertainties in models and developing decision support tools for use by the wind industry that can create power forecasts that effectively incorporate this uncertainty
- Archiving all observations and benchmark model output in a publicly accessible data archive (see "Data Archive and Portal: Making data accessible to the public" sidebar) to engage the broader community in advancing complex-terrain meteorology

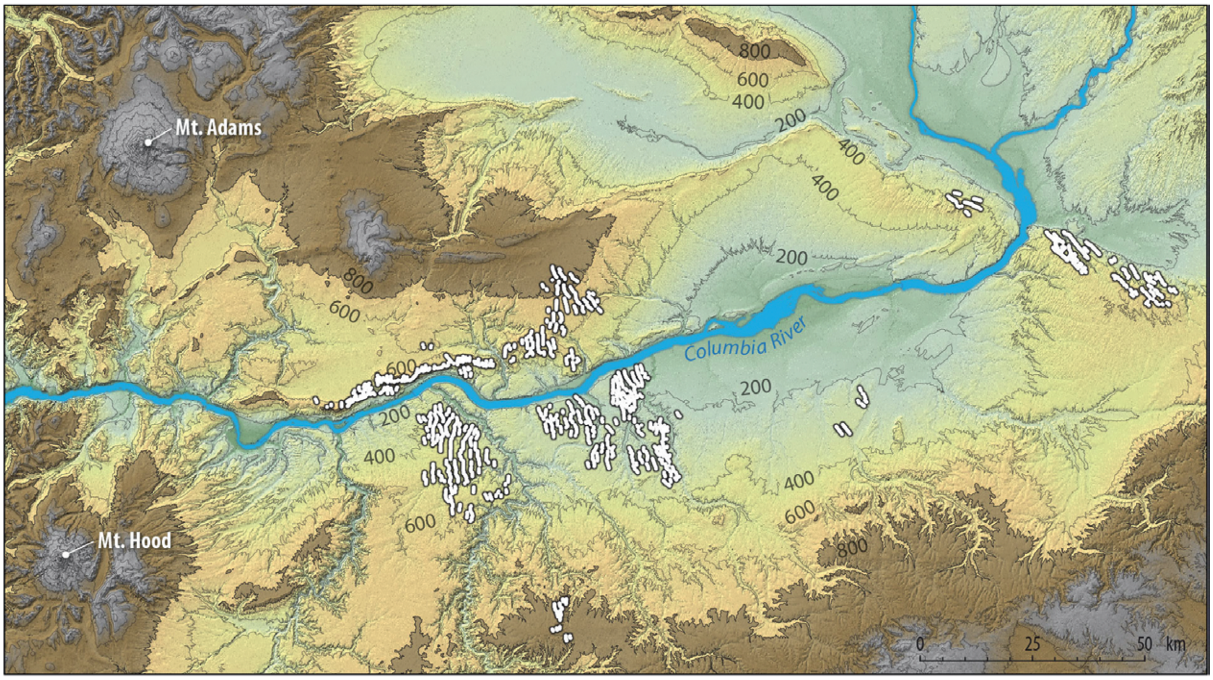

Fig. 1. Primary study region for WFIP2. Terrain rises to the north and south of the Columbia River, which is about 100 m above sea level. The Columbia Gorge passes through the Cascade Mountains (western/left part of the figure), where elevations routinely exceed 1.5 km ASL. Mount Hood and Mount Adams are notable topographic features that exceed 3.4 and 3.7 km in elevation, respectively. Also shown in white are wind turbine locations (data from the U.S. Wind Turbine database: https://eerscmap.usgs.gov/uswtdb/). Elevations of select contours are in meters.

Fig. 2. View in WFIP2 study area looking northwest toward the Columbia River (not visible at lower elevation), showing terrain and wind turbines. Mt. Adams is in the background.

The two main objectives of WFIP2 were to increase understanding of the physical processes and atmospheric properties that affect wind-turbine-height wind speed and direction in areas of complex terrain and to incorporate resulting improved physics into operational weather models. The 0–15-h time frame was the time horizon of focus, with improvements expected in the day-ahead forecast, too. The NWS operationally runs the 13-km horizontal grid spacing, hourly updated Rapid Refresh (RAP) and the 3-km horizontal grid spacing, hourly updated High-Resolution Rapid Refresh (HRRR) weather models, whose outputs are frequently used by industry for predicting wind and solar resources and the power they produce. These models, which are based on variants of the Weather Research and Forecasting (WRF) Model, were targeted for improvement with the intention that validated improvements would be incorporated in the next operational version of the models. A special HRRR nest with 750-m horizontal grid spacing was developed and run over the Columbia basin study area.

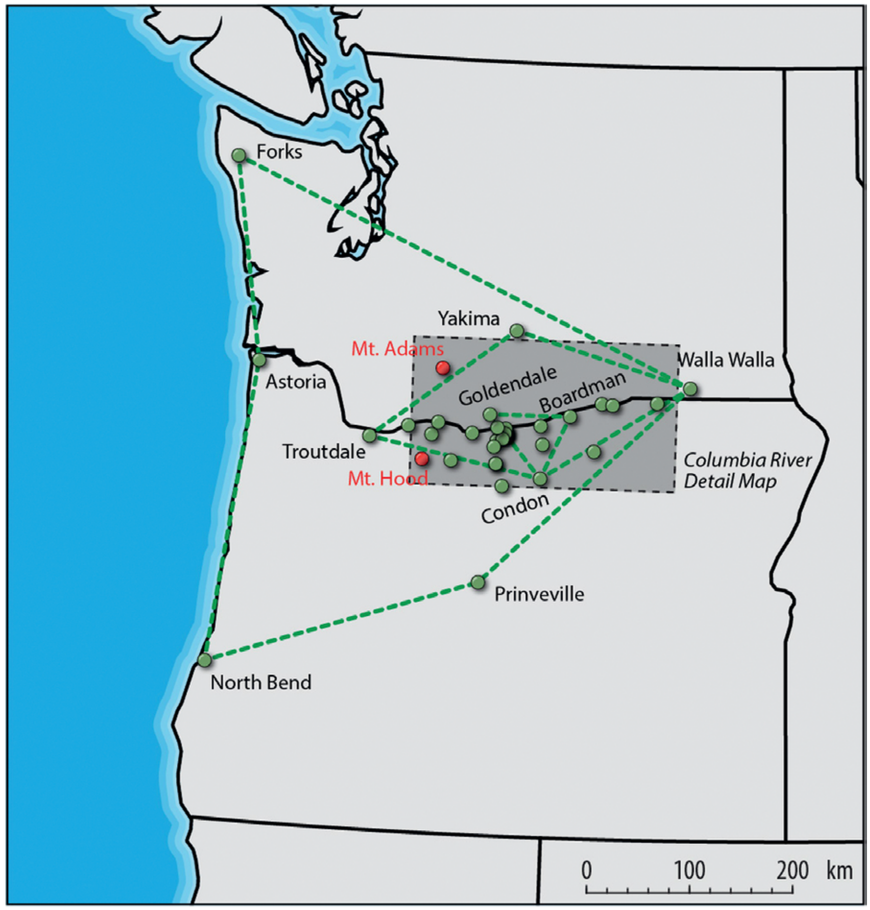

Fig. 3. Illustration of nesting of observations with increasing density at smaller scales in WFIP2 in relation to the U.S. Pacific Northwest. Dashed lines indicate areas of successively smaller scale. The largest scale was anchored by wind profiling radars at Forks and Walla Walla, Washington, and Astoria and North Bend, Oregon. The dark gray shading corresponds to the area depicted in Fig. 1.

The WFIP2 study region's dominant topographical features include the Pacific coast, the Cascade Mountain Range (including several volcanic peaks), the Columbia River basin, and the Columbia River Gorge that cuts through the Cascades linking the coastal plain with the inland basin. (Fig. 1). Figure 2 is a photo taken near the center of Fig. 1. The WFIP2 observational campaign sought to sample winds, stratification, and turbulence across a broad range of spatiotemporal scales to provide insight into key physical processes and observations for model validation, including the operational HRRR model. Therefore, telescoping nests of observations (shown schematically in Fig. 3) were designed: the outer nest encompassing an area from the coast to the eastern edge of the basin, a middle nest focused on the Columbia Gorge and basin, and an inner nest targeting an 80 km × 80 km region near the center of the wind energy production area. Finally, a network of surface flux stations, including an 80-m tower, was deployed in a 2 km × 2 km area, similar to a high-resolution model grid cell, to observe subgrid-scale turbulent processes.

At several supersites, suites of instruments were deployed measuring profiles of winds, temperature, humidity, and radar reflectivity at different vertical resolutions and different height intervals through and above the atmospheric boundary layer. These complementary measurements allowed for a detailed analysis of complex meteorological phenomena and an evaluation of the ability of models (and their parameterization schemes) to accurately reproduce those events. Also, on all of the nests, multiple sites observed turbulence quantities, transcending

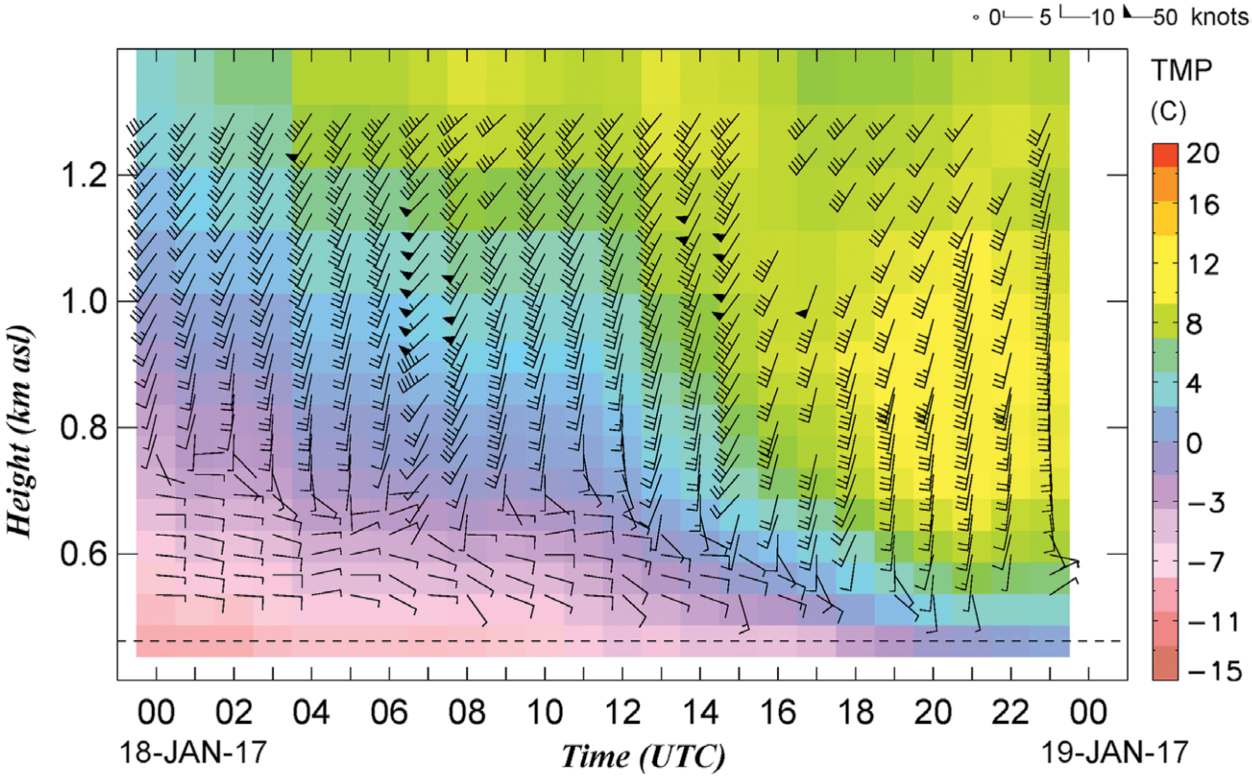

Fig. 4. Mix out of a cold pool in the Columbia basin during WFIP2 as jointly observed by a microwave radiometer and a radar wind profiler. The dashed line indicates the ground level. There is initially a layer of cold air about 400 m deep at the surface with very light easterly winds. Above this layer are very strong south-southwesterly winds associated with an approaching low pressure system. Over a period of 18 h, the high-momentum air aloft scours out the stably stratified cold air in the basin, with much higher wind speeds reaching the altitude of the turbine blades on nearby higher terrain. Such events cause significant upramps in wind power production, but correctly forecasting the timing has been a difficult challenge. [See additional discussion in Olson et al. (2019).]

standard measurements of winds and stratification. Wind forecasts are very sensitive to parameters in boundary layer turbulence parameterizations that can vary seasonally, especially the turbulence dissipation rate (Yang et al. 2017; Berg et al. 2019; McCaffrey et al. 2017; Muñoz-Esparza et al. 2018; Bodini et al. 2018). Several sites thus included capabilities to estimate turbulence dissipation rate throughout the boundary layer.

WFIP2 capitalized on the recent experience of the DOE-funded Experimental Planetary Boundary Layer Instrumentation Assessment (XPIA) campaign Lundquist et al. 2017), which deployed state-of-the-art remote sensing technology, such as scanning lidars and Ka-band radars for quantifying winds using multi-Doppler scanning techniques and microwave radiometers for estimating atmospheric stability. Standard measurements from sonic anemometers on a 300-m meteorological tower quantified the uncertainty of these new types of measurements (Choukulkar et al. 2017; Debnath et al. 2017; Newsom et al. 2017; McCaffrey et al. 2017, Bianco et al. 2017) in preparation for their use in WFIP2. An example of the combination of remote sensing systems to quantify a WFIP2 meteorological event significant for wind energy, in this case cold pool mix out, is shown in Fig. 4. The figure shows the erosion of the cold pool as observed by a collocated microwave radiometer and radar wind profiler.

In addition to the observations provided by members of the WFIP2 team, several external organizations contributed data to this effort (Table 1). For weather events anticipated to be of particular interest, such as cold pool scouring, the NWS added two radiosonde launches per day at their operational sites at Quillayute and Spokane, Washington; Salem and Medford, Oregon; and Boise, Idaho. In aggregate, the NWS committed to providing 200 extra launches to WFIP2. Additionally, power production data were provided by a number of wind plant operators in the Columbia basin under nondisclosure agreements to WFIP2. These data are generally proprietary but are essential to evaluating the impact of improved wind forecasts on electrical power forecasting.

KEY OUTCOMES. A unique aspect of WFIP2 was its 18-month-long, comprehensive set of meteorological observations important for wind energy (Wilczak et al. 2019b). This set of observations, which is freely available to the research community through the Data Archive and Portal (DAP), forms the basis for model development work through a better understanding of the meteorological events and by validation of model simulations. A hierarchy of model development experiments that span an annual cycle was devised to test specific model development efforts as well as the collective impacts of all model physics changes (Olson et al. 2019). This set of experiments includes 1) single case studies, 2) cold-start reforecasts, and 3) fully cycled (data assimilation) tests identical to the operational RAP/HRRR forecast systems. The resulting model improvements were formally validated, and some have been incorporated into NWS foundational weather forecast models. Finally, a tool to provide improved local forecasts of wind ramp events to the wind industry, built on physical forecasts and associated uncertainties, was developed and shared with potential wind industry users (Grimit et al. 2019, in preparation for *Bull. Amer. Meteor. Soc.*).

Case studies. A common set of case studies, selected during the field project, represents the full range of forecasting challenges experienced during the 18-month field study. Model changes were tested in a subset of these case studies and validated against observations. Other analog cases were selected to independently test the model improvements, verifying the generality of the model-physics changes. This work largely drove the model development. Several model components were deemed mature by NOAA's deadline and appropriate to be included in the next operational version of the national weather forecast models. This collection of modifications was advanced to the longer-term testing phase (below).

Year-long reforecasts. This second stage of testing consisted of a full year of twice-daily 24-h reforecasts. Two sets of simulations were performed: 1) a control set of model physics, consisting of the versions of the parameterizations in operational use at the beginning of WFIP2 and 2) an experimental set of physics, consisting of the new or modified set of physical parameterizations. This set of simulations provided a robust benchmark and a measure of success of our preliminary model development tasks.

Fully cycled retrospective test period. A complementary testing framework, more aligned with the full functionality of the RAP and HRRR forecast systems, consisted of hourly updated experiments that included data assimilation of WFIP2 observations. Because of the computational expense of these experiments, only two 10-day retrospective periods were selected, which included the major forecast challenges found in the cool and warm seasons. These tests included hourly cycled RAP and HRRR forecasts run out to 24 h with a very high-resolution nest (horizontal grid spacing of 750 m) run concurrently within the HRRR over the WFIP2 study region. These tests were essential for determining whether the model improvements could be implemented into future operational versions of RAP and HRRR.

Verification and validation. Formal, coordinated verification and validation (V&V) was central to the development and analysis of model improvements and scientific findings within WFIP2. Verification [American Society of Mechanical Engineers (ASME); ASME 2009] is defined as checking the mechanics of the software code, and validation concerns determining the degree to which the model represents the real world for a particular application (i.e., comparison with observations; ASME 2009; Oberkampf and Roy 2010). WFIP2 included the application of tools and methods to enable repeatable, metrics-based assessments of the HRRR model improvements for the analysis of mesoscale weather phenomena that are important for wind energy in the Columbia basin and elsewhere. Verification in WFIP2 was performed with a single-column model to test the impact of isolated code modifications and verify the coding functioned as expected. This process yielded a systematic and quantitative overall assessment of model improvements and information about forecast uncertainties that could be applied in decision support tools for the wind industry.

Improvements transferred to RAP and HRRR. WFIP2 model development efforts were intended to help improve foundational operational forecasts, specifically the RAP and HRRR. WFIP2-related model code changes to the boundary layer, horizontal diffusion, and gravity wave drag schemes were passed into upgraded versions of RAP and HRRR (summer 2018). For example, a revision to the mixing length used to calculate eddy diffusivity based upon a local, or z-less, formulation significantly improved the timing of mix out of cold pools (Olson et al. 2019). In addition, the formulation caused no increase in errors in other regions of the United States or under other weather conditions. Further development efforts will make it into future operational models pending further testing.

WFIP2 model development efforts were also intended to improve community-accessible models such as the WRF Model. Modifications to the Mellor–Yamada–Nakanishi–Niino (MYNN) planetary boundary layer (PBL) scheme and the horizontal diffusion were integrated in version 4.0. Other ongoing WFIP2 development efforts will be integrated into the National Center for Atmospheric Research's (NCAR's) Advanced Research version of WRF (WRF-ARW) repository pending successful testing.

Decision support tools. An important component of WFIP2 was devoted to the investigation of potential impacts on private sector decision-making as a result of the modeling improvements. This portion of the work was driven by two primary questions: 1) How can we convey the possible impacts of complex-terrain phenomena on wind power forecasts, and 2) can we create actionable alerts that will improve situational awareness and reduce decision-making time? Forecast algorithms were developed to target complex-terrain weather phenomena observed during the field campaign that were associated with potentially disruptive power ramping events, like the mix out of cold pools as illustrated in Fig. 4. The algorithm design allowed for fully probabilistic forecasts of the ramp-causing events. The concept was illustrated through a prototype implementation in Vaisala's forecast visualization tools and shared with industry partners from Table 1. Feedback on the concept was encouraging and provided useful avenues for further development of tools to aid the wind industry (Grimit et al. 2019, in preparation for *Bull. Amer. Meteor. Soc.*). The idea is general enough that it could be applied more broadly to other physical phenomena and wind projects elsewhere in the United States.

SUMMARY. WFIP2 was a comprehensive field and modeling study aimed at improving wind forecasts at wind turbine heights in complex terrain. A unique and valuable feature of WFIP2 was the 18-month duration of the comprehensively nested observational component. To our knowledge, no other complex-terrain datasets document this spatial and temporal range to provide opportunities to validate model improvements with comprehensive observations. An additional strength of this study was the collaboration among DOE and NOAA laboratories and industry. Not only were the research teams able to make significant advances in fundamental atmospheric science and addressing shortcomings of subgrid-scale parameterizations and numerical methods, but the engagement of NOAA and industry also provided paths to immediate dissemination of the results to operational users. As a consequence, improved treatments of vertical mixing and surface friction in complex terrain are now included in the NWS operational forecasts. Further, decision support tools have been developed and transferred to the wind energy industry. These tools include both improved modeling and quantification of associated forecast uncertainties in an interface that allows easy visualization of both forecast power ramps and the confidence associated with them.

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REFERENCES

Akish, E., L. Bianco, I. V. Djalalova, J. M. Wilczak, J. Olson, J. Freedman, C. Finley, and J. Cline, 2019: Measuring the impact of additional instrumentation on the skill of numerical weather prediction models at forecasting wind ramp events during the first Wind Forecast Improvement Project (WFIP). *Wind Energy*, https://doi.org/10.1002/we.2347, in press.

Armstrong, A., R. R. Burton, S. E. Lee, S. Mobbs, N. Ostle, V. Smith, S. Waldron, and J. Whitaker, 2016: Ground-level climate at a peatland wind farm in Scotland is affected by wind turbine operation. *Environ. Res. Lett.*, **11**, 44024, https://doi.org/10.1088/1748-9326/11/4/044024.

Arthur, R. S., K. A. Lundquist, J. D. Mirocha, and F. K. Chow, 2018: Topographic effects on radiation in the WRF Model with the immersed boundary method: Implementation, validation, and application to complex terrain. *Mon. Wea. Rev.*, **146**, 3277–3292, https://doi.org/10.1175/MWR-D-18-0108.1.

ASME, 2009: Standard for verification and validation in computational fluid dynamics and heat transfer. ASME Rep. V V 20-2009, 88 pp.

Baidya Roy, S., and J. J. Traiteur, 2010: Impacts of wind farms on surface air temperatures. *Proc. Natl. Acad. Sci. USA*, **107**, 17 899–17 904, https://doi.org/10.1073/pnas.1000493107.

Berg, L. K., Y. Liu, B. Yang, Y. Qian, J. Olson, P.-L. Ma and Z. Hou, 2019: Sensitivity of turbine-height wind speeds to parameters in planetary boundary-layer in the Weather Research and Forecasting Model: Extension to wintertime conditions. *Bound.-Layer Meteor.*, **170**, 507–518, https://doi.org/10.1007/s10546-018-0406-y.

Bianco, L., I. V. Djalalova, J. M. Wilczak, J. Cline, S. Calvert, E. Konopleva-Akish, C. Finley, and J. Freedman, 2016: A wind energy ramp tool and metric for measuring the skill of numerical weather prediction models. *Wea. Forecasting*, **31**, 1137–1156, https://doi.org/10.1175/WAF-D-15-0144.1.

——, K. Friedrich, J. M. Wilczak, D. Hazen, D. Wolfe, R. Delgado, S. P. Oncley, and J. K. Lundquist, 2017: Assessing the accuracy of microwave radiometers and radio acoustic sounding systems for wind energy applications. *Atmos. Meas. Tech.*, **10**, 1707–1721, https://doi.org/10.5194/amt-10-1707-2017.

Bodini, N., J. K. Lundquist, and R. K. Newsom, 2018: Estimation of turbulence dissipation rate and its variability from sonic anemometer and wind Doppler lidar during the XPIA field campaign. *Atmos. Meas. Tech.*, **11**, 4291–4308, https://doi.org/10.5194/amt-2018-80.

Bougeault, P., and Coauthors, 2001: The MAP special observing period. *Bull. Amer. Meteor. Soc.*, **82**, 433–462, https://doi.org/10.1175/1520-0477(2001)082<0433:TMSOP>2.3.CO;2.

Choukulkar, A., and Coauthors, 2017: Evaluation of single and multiple Doppler lidar techniques to measure complex flow during the XPIA field campaign. *Atmos. Meas. Tech.*, **10**, 247–264, https://doi.org/10.5194/amt-10-247-2017.

Clements, W. E., J. A. Archuleta, and P. H. Gudiksen, 1989: Experimental design of the 1984 ASCOT field study. *J. Appl. Meteor.*, **28**, 405–413, https://doi.org/10.1175/1520-0450(1989)028<0405:EDOTAF>2.0.CO;2.

Coulter, R. L., and T. J. Martin, 1996: Effects of stability on the profiles of vertical velocity and its variance in katabatic flow. *Bound.-Layer Meteor.*, **81**, 23–33, https://doi.org/10.1007/BF00119397.

Debnath, M., and Coauthors, 2017: Assessment of virtual towers performed with scanning wind lidars and Ka-band radars during the XPIA experiment. *Atmos. Meas. Tech.*, **10**, 1215–1227, https://doi.org/10.5194/amt-10-1215-2017.

Di Sabatino, S., 2016: Boundary-layer atmospheric processes in mountainous terrain: Results from MATERHORN-X. *Bound.-Layer Meteor.*, **159**, 465–467, https://doi.org/10.1007/s10546-016-0131-3.

DOE, 2012: Complex flow. DOE Wind Program Workshop Rep., 122 pp., www.energy.gov/sites/prod/files/2013/12/f5/complex_flow_workshop_report.pdf.

——, 2015: Wind vision: A new era for wind power in the United States. National Renewable Energy Laboratory Rep., 348 pp., www.nrel.gov/docs/fy15osti/63197-2.pdf.

——, 2018a: Today in energy. Energy Information Administration, accessed 2 May 2018, www.eia.gov/todayinenergy/detail.php?id=35412.

——, 2018b: Electric power monthly with data for December 2017. Energy Information Administration Rep., 258 pp., www.eia.gov/electricity/monthly/archive/february2018.pdf.

Doran, J. C., J. D. Fast, and J. Horel, 2002: The VTMX 2000 campaign. *Bull. Amer. Meteor. Soc.*, **83**, 537–551, https://doi.org/10.1175/1520-0477(2002)083<0537:TVC>2.3.CO;2.

Fernando, H. J. S., and Coauthors, 2015: The MATERHORN: Unraveling the intricacies of mountain weather. *Bull. Amer. Meteor. Soc.*, **96**, 1945–1967, https://doi.org/10.1175/BAMS-D-13-00131.1.

——, J. K. Lundquist, and S. Oncley, 2017: Monitoring wind in Portugal's mountains down to microscales. *Eos, Trans. Amer. Geophys. Union*, **98**, https://doi.org/10.1029/2017EO074745.

Fitch, A. C., J. B. Olson, J. K. Lundquist, J. Dudhia, A. K. Gupta, J. Michalakes, and I. Barstad, 2012: Local and mesoscale impacts of wind farms as parameterized in a mesoscale NWP model. *Mon. Wea. Rev.*, **140**, 3017–3038, https://doi.org/10.1175/MWR-D-11-00352.1.

——, J. K. Lundquist, and J. B. Olson, 2013: Mesoscale influences of wind farms throughout a diurnal cycle. *Mon. Wea. Rev.*, **141**, 2173–2198, https://doi.org/10.1175/MWR-D-12-00185.1.

Haupt, S. E., and Coauthors, 2019: On bridging a modeling scale gap: Mesoscale to microscale coupling for wind energy. *Bull. Amer. Meteor. Soc.*, https://doi.org/10.1175/BAMS-D-18-0033.1, in press.

Jiménez, P. A., J. Navarro, A. M. Palomares, and J. Dudhia, 2015: Mesoscale modeling of offshore wind turbine wakes at the wind farm resolving scale: A composite-based analysis with the Weather Research and Forecasting Model over Horns Rev. *Wind Energy*, **18**, 559–566, https://doi.org/10.1002/we.1708.

Lee, J. C. Y., and J. K. Lundquist, 2017: Evaluation of the wind farm parameterization in the Weather Research and Forecasting Model (version 3.8.1) with meteorological and turbine power data. *Geosci. Model Dev.*, **10**, 4229–4244, https://doi.org/10.5194/gmd-10-4229-2017.

Lehner, M., and M. W. Rotach, 2018: Current challenges in understanding and predicting transport and exchange in the atmosphere over mountainous terrain. *Atmosphere*, **9**, 276, https://doi.org/10.3390/atmos9070276.

Lundquist, J. K., and Coauthors, 2017: Assessing state-of-the-art capabilities for probing the atmospheric boundary layer: The XPIA field campaign. *Bull. Amer. Meteor. Soc.*, **98**, 289–314, https://doi.org/10.1175/BAMS-D-15-00151.1.

——, K. K. DuVivier, D. T. Kaffine, and J. M. Tomaszewski, 2018: Costs and consequences of wind turbine wake effects arising from uncoordinated wind energy development. *Nat. Energy*, **4**, 26–34, https://doi.org/10.1038/s41560-018-0281-2.

Mann, J., and Coauthors, 2018: Complex terrain experiments in the New European Wind Atlas. *Philos. Trans. Roy. Soc.*, **375A**, https://doi.org/10.1098/rsta.2016.0101.

Marquis, M., J. Wilczak, M. Ahlstrom, J. Sharp, A. Stern, J. Smith, and S. Calvert, 2011: Forecasting the wind to reach significant penetration levels of wind energy. *Bull. Amer. Meteor. Soc.*, **92**, 1159–1171, https://doi.org/10.1175/2011BAMS3033.1.

McCaffrey, K., and Coauthors, 2017: Identification of tower-wake distortions using sonic anemometer and lidar measurements. *Atmos. Meas. Tech.*, **10**, 393–407, https://doi.org/10.5194/amt-10-393-2017.

Mirocha, J. D., and K. A. Lundquist, 2017: Assessment of vertical mesh refinement in concurrently nested large-eddy simulations using the Weather Research and Forecasting Model. *Mon. Wea. Rev.*, **145**, 3025–3048, https://doi.org/10.1175/MWR-D-16-0347.1.

Muñoz-Esparza, D., R. D. Sharman, and J. K. Lundquist, 2018: Turbulence dissipation rate in the atmospheric boundary layer: Observations and WRF mesoscale modeling during the XPIA field campaign. *Mon. Wea. Rev.*, **146**, 351–371, https://doi.org/10.1175/MWR-D-17-0186.1.

Newsom, R. K., W. A. Brewer, J. M. Wilczak, D. E. Wolfe, S. P. Oncley, and J. K. Lundquist, 2017: Validating precision estimates in horizontal wind measurements from a Doppler lidar. *Atmos. Meas. Tech.*, **10**, 1229–1240, https://doi.org/10.5194/amt-10-1229-2017.

Nygaard, N. G., 2014: Wakes in very large wind farms and the effect of neighbouring wind farms. *J. Phys. Conf. Ser.*, **524**, 012162, https://doi.org/10.1088/1742-6596/524/1/012162.

Oberkampf, W., and C. Roy, 2010: *Verification and Validation in Scientific Computing.* Cambridge University Press, 782 pp.

Olson, J. B., and Coauthors, 2019: Improving wind energy forecasting through numerical weather prediction model development. *Bull. Amer. Meteor. Soc.*, https://doi.org/10.1175/BAMS-D-18-0040.1, in press.

Orgill, M. M., and R. I. Schreck, 1985: An overview of the ASCOT multi-laboratory field experiments in relation to drainage winds and ambient flow. *Bull. Amer. Meteor. Soc.*, **66**, 1263–1277, https://doi.org/10.1175/1520-0477(1985)066<1263:AOOTAM>2.0.CO;2.

Rai, R. K., L. K. Berg, W. J. Shaw, B. Kosovic, J. D. Mirocha, and B. L. Ennis, 2017: Study of the spatiotemporal variability over complex terrain using turbulent kinetic energy budget in the convective boundary layer. *J. Appl. Meteor. Climatol.*, **56**, 3285–3302, https://doi.org/10.1175/JAMC-D-17-0124.1.

Rajewski, D. A., and Coauthors, 2013: Crop Wind Energy Experiment (CWEX): Observations of surface-layer, boundary layer, and mesoscale interactions with a wind farm. *Bull. Amer. Meteor. Soc.*, **94**, 655–672, https://doi.org/10.1175/BAMS-D-11-00240.1.

——, E. S. Takle, J. K. Lundquist, J. H. Prueger, R. L. Pfeiffer, J. L. Hatfield, K. K. Spoth, and R. K. Doorenbos, 2014: Changes in fluxes of heat, H_2O, and CO_2 caused by a large wind farm. *Agric. For. Meteor.*, **194**, 175–187, https://doi.org/10.1016/j.agrformet.2014.03.023.

Schreck, S., J. Lundquist, and W. Shaw, 2008: U.S. Department of Energy workshop report—Research needs for wind resource characterization. National Renewable Energy Laboratory Rep. TP-500-43521, 116 pp.

Serafin, S., and Coauthors, 2018: Exchange processes in the atmospheric boundary layer over mountainous terrain, *Atmosphere*, **9**, 102, https://doi.org/10.3390/atmos9030102.

Shaw, W. J., S. J. Schreck, and J. K. Lundquist, 2009: Research needs for wind resource characterization. *Bull. Amer. Meteor. Soc.*, **90**, 535–538, https://doi.org/10.1175/2008BAMS2729.1.

Siedersleben, S. K., and Coauthors, 2018: Evaluation of a wind farm parametrization for mesoscale atmospheric flow models with aircraft measurements. *Meteor. Z.*, **27**, 401–415, https://doi.org/10.1127/metz/2018/0900.

Smith, C. M., R. J. Barthelmie, and S. C. Pryor, 2013: In situ observations of the influence of a large onshore wind farm on near-surface temperature, turbulence intensity and wind speed profiles. *Environ. Res. Lett.*, **8**, 034006, https://doi.org/10.1088/1748-9326/8/3/034006.

Volker, P. J. H., J. Badger, A. N. Hahmann, and S. Ott, 2015: The Explicit Wake Parametrisation V1.0: A wind farm parametrisation in the mesoscale model WRF. *Geosci. Model Dev.*, **8**, 3715–3731, https://doi.org/10.5194/gmd-8-3715-2015.

Wilczak, J., and Coauthors, 2015: The Wind Forecast Improvement Project (WFIP): A public–private partnership addressing wind energy forecast needs. *Bull. Amer. Meteor. Soc.*, **96**, 1699–1718, https://doi.org/10.1175/BAMS-D-14-00107.1.

——, and Coauthors, 2019a: Data assimilation impact of in situ and remote sensing meteorological observations on wind power forecasts during the first Wind Forecast Improvement Project (WFIP). *Wind Energy*, **22**, 932–944, https://doi.org/10.1002/we.2332.

——, and Coauthors, 2019b: The Second Wind Forecast Improvement Project (WFIP2): Observational field campaign. *Bull. Amer. Meteor. Soc.*, **100**, 1701–1723, https://doi.org/10.1175/BAMS-D-18-0035.1.

Wildmann, N., N. Vasiljevic, and T. Gerz, 2018: Wind turbine wake measurements with automatically adjusting scanning trajectories in a multi-Doppler lidar setup. *Atmos. Meas. Tech.*, **11**, 3801–3814, https://doi.org/10.5194/amt-11-3801-2018.

Wyngaard, J. C., 2004: Toward numerical modeling in the “terra incognita.” *J. Atmos. Sci.*, **61**, 1816–1826, https://doi.org/10.1175/1520-0469(2004)061<1816:TNMITT>2.0.CO;2.

Yang, B., and Coauthors, 2017: Sensitivity of turbine-height wind speeds to parameters in planetary boundary-layer and surface-layer schemes in the Weather Research and Forecasting Model. *Bound.-Layer Meteor.*, **162**, 117–142, https://doi.org/10.1007/s10546-016-0185-2.

Zhou, L., Y. Tian, S. Baidya Roy, C. Thorncroft, L. F. Bosart, and Y. Hu, 2012: Impacts of wind farms on land surface temperature. *Nat. Climate Change*, **2**, 539–543, https://doi.org/10.1038/nclimate1505.

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