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Development and Evaluation of High Resolution Simulation Tools to Improve Fire Weather Forecasts

Brian K. Lamb
Washington State University

Jason M. Forthofer
USDA Forest Service

Peter R. Robichaud
USDA Forest Service

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JFSP Project Title: Development and Evaluation of High Resolution Simulation Tools to Improve Fire Weather Forecasts

Principal Investigator: Brian K. Lamb[a]

Co-Principal Investigator: Jason M. Forthofer[b]

Federal Cooperator: Peter R. Robichaud[c]

Affiliations: [a]Washington State University, Laboratory for Atmospheric Research; [b]USDA Forest Service, Missoula Fire Sciences Laboratory, Missoula, MT; [c]USDA Forest Service, Rocky Mountain Research Station, Moscow, ID;

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I. Abstract

Fire weather forecasts rely on numerical weather simulations where the grid size is 4 km x 4 km or larger. In areas of complex terrain, this model resolution will not capture the details of wind flows associated with complicated topography. Wind channeling in valleys, wind speed-up over mountains and ridges, and enhanced turbulence associated with rough terrain and tall forest canopies are poorly represented in current weather model applications. A number of numerical wind flow models have been developed for simulating winds at high resolution; however, there are limited observational data available at the spatial scales appropriate for evaluating these types of models. In response to this need for high resolution validation data, we collected wind measurements at very high spatial resolution over a range of meteorological conditions from three different types of terrain/landcover features: an isolated mountain covered predominantly by grass and sagebrush, a steep river canyon covered predominantly by grass, and a dissected montane drainage with a tall forest canopy. We used data from the isolated mountain and the steep river canyon to evaluate surface wind predictions from routine weather forecasts and a high resolution wind simulation model, WindNinja, developed specifically for fire behavior applications. Data from the third field site will be used for future model evaluations planned to investigate the effect of tall forest canopies on surface wind predictions.

Analyses of observations from the isolated mountain and steep river canyon sites indicate that operational weather model (i.e., with numerical grid resolutions of around 4 km or larger) wind predictions are not likely to be good predictors of local near-surface winds (i.e., at sub-grid scales) in complex terrain. Under periods of weak synoptic forcing, surface winds tended to be decoupled from large-scale flows, and under periods of strong synoptic forcing, variability in surface winds was sufficiently large due to terrain-induced mechanical effects that a large-scale mean flow would not be representative of surface winds at most locations on or within the terrain feature. These findings are reported in a manuscript titled “High Resolution Observations of the Near-Surface Wind Field over an Isolated Mountain and in a Steep River Canyon” submitted for publication in Atmospheric Chemistry and Physics. Links to the observed data from this effort as well as an online interface to query, visualize, summarize, and download subsets of the data are available at: http://www.firemodels.org/index.php/windninja-introduction/windninja-publications.

Findings from the model evaluations work indicate that using WindNinja to downscale from numerical weather prediction (NWP) model winds can, in some cases, improve the accuracy of surface wind forecasts in complex terrain. Predictions of surface wind speeds and directions improved with downscaling via WindNinja when flow features induced by large scale effects were adequately captured by the NWP model used to initialize WindNinja. This suggests that WindNinja could be incorporated into current fire forecast methods to provide better short-term forecasts for fire management operations. These findings are reported in a manuscript titled “Downscaling Surface Wind Predictions from Numerical Weather Prediction Models in Complex Terrain with a Mass-consistent Wind Model” that will be submitted to the Journal of Applied Meteorology and Climatology later this spring.

II. Background and Purpose

Near-surface winds are important for forecasting wildfire behavior and spread. These near-surface winds are difficult to predict in regions where rugged terrain and/or vegetation have a significant effect on the local flow field. Terrain effects such as wind speed-up over ridges, flow channeling in valleys, flow separation around terrain obstacles, enhanced surface roughness, and local surface heating and cooling alter the flow field over spatial scales finer than those typically used by mesoscale numerical weather prediction (NWP) models. NWP models used for routine forecasting typically employ grids with horizontal resolutions of 4 km or larger and are generally restricted to grid resolutions of greater than around 1 km (Lundquist et al. 2010; Mahrer 1984). This is a significant limitation of NWP forecasts for wildfire spread and behavior applications. A 1 km spatial resolution is coarse compared to the scales over which spatially varying terrain can impart effects on the local wind flow and, in many cases, is not sufficient to resolve important features in the flow relevant to fire spread and behavior.

Dynamic downscaling is one option for improving coarse scale winds from routine NWP model forecasts. It has been shown that NWP forecasts linked with higher-resolution diagnostic wind simulation models can produce more accurate wind predictions in complex terrain (Beaucage et al. 2012). There are two types of diagnostic models commonly used for downscaling NWP winds to higher resolution: computational fluid dynamic (CFD) models and mass-conserving models. CFD models solve the conservation of mass and momentum equations to obtain a flow solution that accounts for turbulent kinetic energy (TKE) in the flow field. The limitations to the CFD approach are that even the fastest solutions require significant computational resources and simulation time and their operation typically requires technical expertise (to properly set up boundary conditions, select a turbulence model, etc.), which many users do not have.

Mass-conserving models solve the conservation of mass equation, but do not include a momentum equation, and thus, offer a reduced-physics approach to solve for the mean flow field. Because of this simplification, mass-conserving models are very fast compared to CFD flow solutions. Some accuracy is lost due to neglect of momentum in the flow solution, particularly in areas of flow separation, such as on the lee side of terrain features; however, mean flow solutions generated by mass-conserving models have been shown to generate accurate predictions in other regions such as on the windward side of terrain features, where speed-up occurs (Forthofer et al. In Review). Parameterizations for thermal effects, such as non-neutral atmospheric stability and diurnal slope flows, can also be included within the mass-conserving equations to improve accuracy. Ultimately, the significant reduction in computational resources and simulation time make mass-conserving models a good option for time-critical applications, such as support of wildfire operations. In this work, we evaluate a mass-conserving diagnostic wind model, WindNinja (Forthofer et al. In Review; Forthofer 2007), for dynamically downscaling NWP model winds in complex terrain. WindNinja was developed specifically for use in fire spread and behavior modeling and thus, is fast-running, requires simple user inputs, lightweight computational resources, and essentially no technical expertise to operate.

High-resolution diagnostic wind models like WindNinja are difficult to evaluate, however, due to the lack of high resolution surface wind data available in observational data sets. Existing observational datasets are limited in terms of the types of terrain features and range of meteorological conditions represented. For example, previous evaluations of WindNinja performed by Forthofer et al. (In Review) were limited to observations from two relatively simple-geometry hills. In fact, the two most widely used datasets for evaluation of high resolution diagnostic wind models were collected on topographically-simple, low elevation hills investigated for wind energy applications (Berg et al., 2011; Taylor and Teunissen, 1987). Data collected for wind energy research has come from relatively simple terrain, likely because winds in more complicated terrain are more difficult to reliably forecast and have higher turbulence which reduces the life of the turbines, making complicated terrain less appealing for turbine siting. These studies from idealized field sites for wind energy research represent relatively gentle terrain compared to the wide range of regions where terrain-induced winds occur. As a result, these data do not provide sufficient test data for evaluating spatial representation of modeled flows for the types of terrain features in areas where wildfires commonly occur, such as isolated terrain obstacles with complex geometries, dissected montane environments, and steep river canyons. Examples of the types of flow phenomenon that are of interest for high resolution model evaluations include 1) local surface layer flow decoupling from larger-scale atmospheric flow, 2) diurnal slope flows; 3) mountain-valley flows; 4) mountain-plain flows; and 4) the interactions of these effects at multiple spatial and temporal scales.

In response to this need for high resolution surface wind data for evaluations of diagnostic wind models, we collected wind data from three types of terrain features: 1) an isolated mountain, 2) a steep river canyon, and 3) a dissected montane drainage with a tall forest canopy. We then used data from the isolated mountain site and the steep river canyon site to evaluate the WindNinja model for use in downscaling NWP winds.

A. Project Objectives

The overall goal of this work was to evaluate the accuracy of existing high resolution wind models applied to complex terrain and to determine how these tools could be used to improve fire weather forecasts. Specific objectives to achieve this goal were:

1. Collect high resolution wind data from three field sites, each of which exhibits a different type of complex terrain feature.
2. Compare output from NWP forecasts and from high resolution wind models with the observed wind data to assess model ability in predicting accurate wind fields above the investigated terrain features.
3. Incorporate changes to the high resolution tools to improve their performance and to improve their usability as standard tools.
4. Evaluate methods for incorporating these high resolution weather models with current forecast models to generate a more detailed and accurate fire forecasts.

III. Study Description and Location

Field Sites

<u>Big Southern Butte (BSB)</u>: BSB is a volcanic dome cinder cone approximately 4 km wide that rises 800 m above the Upper Snake River Plain (USRP) in southeastern Idaho (43.395958, -113.02257). The dominant vegetation on the USRP and BSB is grass and sagebrush (generally < 1 m tall), although a few north-facing slopes on the butte have some timber. Average slopes range from 30 to 40% with nearly vertical cliffs in some locations. The USRP is essentially flat terrain surrounding BSB and extends more than 120 km to the north, east, south, and southwest. The USRP is bordered by tall mountain ranges to the northwest and southeast. There are three prominent drainages (Big Lost River, Little Lost River, and Birch Creek) that flow southeast onto the USRP to the north and northeast of BSB. These mountain-valley features contribute to thermally-driven diurnal flows and formation of convergence zones on the USRP. Nighttime down-drainage flows on the USRP are from the northeast and daytime up-drainage flows are from the southwest.

<u>Salmon River Canyon (SRC)</u>: The field site was a 5 km long stretch of river located approximately 20 km east (upstream) of Riggins, ID (45.401667, -116.22667) and spanning in elevation from the canyon bottom (550 m) to the ridgetops (1600 m). The river canyon follows a nearly straight east-west path within this extent. Prevailing winds in this region are from the west. The predominant vegetation is grass (generally < 0.5 m tall), with some timber in the higher elevations on the north aspects. Our instrumentation was deployed away from forested areas, so as to avoid effects of the forest canopy on the wind flow. There were prominent side drainages entering SRC on the east and west end of our study area.

<u>Priest River Experimental Forest (PREF)</u>: PREF is located on a westward slope of a spur of the Selkirk Mountains, approximately 20 km north of Priest River, ID. The field site was located in the

Benton Creek watershed (48.351667, -116.809167), which runs predominantly east-west, spanning approximately 5.7 km from east to west and 1.5 km from north to south. Elevations range from 670 m at the western boundary of PREF to 1800 m at the eastern boundary. Slopes generally range from 30 to 70%. The majority of PREF is covered by old-growth mixed conifer forest, including Western redcedar (*Thuja plicata*), Douglas fir (*Pseudotsuga menzieii*), Ponderosa pine (*Pinus ponderosa*), Western larch (*Larix occidentalis*), and Engelmann spruce (*Picea engelmannii*). Canopy height ranges from 25 to 60 m. Prevailing winds in this region are from the southwest.

Data Collection and Sampling

Each field site was instrumented with a network of surface wind sensors deployed over a several month period and supplemented with short term deployment of sonic anemometers and ground-based vertical profiling instruments. Spatially dense arrays of more than 50 cup-and-vane anemometers (S-WCA-M003, Onset Computer Corporation) measured wind speeds and directions at 3.3 m AGL to characterize surface flow patterns over and within the terrain features. Wind speed and direction data were measured at 1 Hz and 30-second average wind speeds, peak gusts, and average directions were recorded. These surface measurements were complemented by sonic anemometers (CSAT3, Campbell Scientific, Inc.; SATI/3Vx, Applied Technologies, Inc.) and vertical profiling instruments (MFAS, Scintech) at select locations and times in order to provide measures of turbulence, friction velocity, and sensible heat flux in near surface flows as well as to characterize flows aloft. Radiosonde (iMet-1, International Met Systems) launches were conducted to characterize large-scale flows aloft for select time periods at each site. Weather stations (WXT520, Vaisala) measured 2-m AGL relative humidity, air temperature, wind speed and direction, solar radiation, and precipitation at select locations at SRC and PREF.

Additionally, the National Oceanic and Atmospheric Administration Field Research Division (NOAA-FRD) operates a permanent mesonet system that consists of 35 towers spread across the USRP and encompassing the BSB study area (http://www.noaa.inel.gov/capabilities/mesonet/mesonet.htm; http://niwc.noaa.inel.gov/). The mesonet towers measure wind speed, wind direction, air temperature, relative humidity, and solar radiation. NOAA-FRD operates a permanent wind profiling system (915 MHz radar profiler) and radio acoustic sounding system (RASS) at a location approximately 10 km northeast of BSB. NOAA-FRD also operated a mobile Radian Model 600PA sodar approximately 5 km south of BSB and an Atmospheric Systems Corp. (ASC) Model 4000 mini sodar 15 km south of BSB 15 July to 18 July, 2010 and 31 August to 2 September, 2010.

The sampling layouts were designed to obtain measures of the upwind approach flows as well as perturbations to the approach flow associated with the terrain features. For each site, the extent of the sensor array covered an area that spanned one to several mesoscale weather forecast grids of typical routine forecast resolution (4 to 12 km) and the spatial density of the surface sensors was fine enough to resolve flow patterns at the sub-grid scale.

<u>BSB</u>: An array of 53 surface sensors was deployed between 15 June 2010 to 9 September 2010. Sensors were deployed along two transects running southwest to northeast. A number of randomly located sensors were added along and outside the two transects to increase the spatial coverage on and around the butte. A sodar profiler was deployed 2 km southwest of the butte from 1 July to 18 July, 2010 and immediately northeast of the butte from 31 August to 1 September, 2010. A tower of sonic anemometers was deployed 2 km southwest of the butte from 14 July to 18 July, 2010. Three RadioSonde launches were conducted at BSB from 31 August to 2 September, 2010.

<u>SRC</u>: An array of 27 surface sensors was deployed in three cross-river transects from 14 July to 13 September, 2011. Sodars and sonic anemometers were operated from 16 July to 18 July and 29 August to 31 August, 2011. Sodars were located in the valley bottom on the north side of the river and at the ridgetop on the north side of the river near the east end of the field site. Sonics were operated on north and south ridgetops near the west end of the study area and at two locations in the valley bottom on the north side of the river. Two weather stations monitored air temperature, relative humidity, precipitation, solar radiation, wind speed, and wind direction; one was located on the southern ridgetop at the east end

of the field site and the other was located in the valley bottom on the north side of the river. Six RadioSonde launches were conducted on 18 August, 2011.

PREF: The PREF site was substantially different from the other sites, due to the presence of the tall forest canopy, and thus, the surface sensor deployment strategy was slightly modified. We deployed an array of 15 surface sensors along three north-south transects spanning the Benton Creek drainage during September 16–December 20, 2011. Sensors were located both above and within the canopy. Six surface sensors were located above the canopy by attaching the pole-mounted sensors to the trunk of the tree near the tree-top, such that the anemometer protruded as far as possible above the canopy. Trees for sensor mountings were selected to be the tallest trees in the area, so as to ensure that the mounted sensors were are far above the average canopy height as possible. Ground-based surface sensors were located in close proximity to the tree-mounted sensors in order to provide a measure of the canopy effect on the wind flow. Sodars were operated in the bottom of the drainage at the western boundary of PREF and near the top of the drainage near the eastern boundary during October 5-7, 2011. A sonic anemometer was operated at the top of the drainage near the eastern boundary during September 16-December 20, 2011. A series of four RadioSonde launches were conducted between October 5-7, 2011.

Data Analysis

The surface wind data were partitioned into four distinct wind regimes in order to facilitate model evaluations during periods of weak synoptic forcing (typical diurnal flows) and periods of strong synoptic forcing (high wind events). The four wind regimes are:

1. a downslope regime, which included downslope and downvalley flows, forced by nighttime surface cooling under weak synoptic forcing
2. an upslope regime, which included upslope and upvalley flows, forced by daytime surface heating under weak synoptic forcing
3. an afternoon regime, during which local flows were influenced by larger scale flows, either through convective mixing (at BSB) or through formation of upvalley drainage winds (at SRC) under weak synoptic forcing
4. a synoptically forced regime, during which the normal diurnal cycle was disrupted by strong larger scale flows and local flows typically correlated with gradient level winds due to mechanically-induced turbulent mixing in the boundary layer.

The following procedure was used to partition the surface data into these flow regimes. First, periods during which the wind speed exceeded a threshold wind speed at a surface sensor chosen to be representative of the large-scale flow at each site were partitioned into regime 4. Threshold wind speeds were selected for each site based on visual inspection of the wind speed time series data for the chosen sensors. Thresholds were selected to be speeds that were just above the typical daily peak speed for the chosen sensors. In other words, the threshold speed was only exceeded when synoptic forcing disrupted the typical diurnal wind regime at a given site. Speeds below the threshold are indicative of periods of weak synoptic forcing, during which the diurnal wind regime prevails.

After filtering out the synoptically driven periods, the remaining data were then partitioned into regimes 1–3 based on visual inspection of hourly vector maps (described below). Periods which exhibited clearly defined downslope flow were partitioned into regime 1. Periods which exhibited clearly defined upslope flow were partitioned into regime 2. And afternoon periods during which the upslope regime was disturbed were partitioned into regime 3.

Hourly vector maps were used to visualize the spatial patterns of the wind fields for classifying flow regimes. The vector maps were produced by partitioning the hourly data into one of two categories, periods of strong synoptic forcing or periods of weak synoptic forcing, and then averaging the hourly data (for each sensor) within each category over the entire monitoring period. The result is an hourly average wind vector at each sensor location for each flow category. For example, a vector map for 1300 under weak synoptic forcing would be produced by filtering out the periods of strong synoptic forcing and then averaging all hourly flow data for the 1300 hour at each sensor.

All data analysis and visualization was performed in R (R Core Team, 2013). Vector maps were produced using the ggmap library (Kahle and Wickam, 2013).

Model Evaluations

Surface wind predictions from four NWP forecasts were evaluated. All four NWP models are Weather Research and Forecasting (WRF)-based models, but with different configurations (e.g., numerical cores, grid resolutions, initial conditions, boundary layer schemes, etc.; Table 1). Wind predictions from all four NWP models were dynamically downscaled with WindNinja. The full suite of models used for evaluations was:

1. WRF-NARR – WRF runs with North American Regional Reanalysis data (Mesinger et al. 2006)
2. WRF-UW – routine forecast WRF runs from the University of Washington
3. NAM – North American Mesoscale Mode
4. HRRR – High Resolution Rapid Refresh.
5. NWP winds (i.e., 1-4) downscaled with WindNinja

Table 1. Model specifications. When values differ between sites, values for SRC are in parentheses.

Model	Horizontal grid resolution	Numerical core	Run frequency
NAM	12 km	NMM	00z, 06z, 12z, 18z
WRF-UW	4 km	ARW	00z, 12z
HRRR	3 km	ARW	hourly
WRF-NARR	1.33 km	ARW	NA
WindNinja[b]	138 (54) m	NA	NA

[b] WindNinja horizontal grid resolution depends on the resolution and extent of the digital elevation model used for the simulation.

Predictions from all models were evaluated with the surface wind data collected from BSB and SRC. Observed wind speed and direction data were averaged over a 10-min period at the top of each hour for comparison to hourly NWP forecasts. A five-day period was chosen at each site for model evaluations. July 15-19 2010 was chosen for BSB and August 15-19 2011 was chosen for SRC. These specific periods were chosen because they included periods of both strong and weak synoptic forcing, conditions were consistently relatively dry and sunny, complementary vertical profiling observations were available, and they were periods for which we were able to acquire forecasts from all NWP models selected for investigation in this study. Hours of upslope, downslope, and synoptically-driven conditions were partitioned out of this five-day period at each site to further evaluate predictions under these particular types of flow regimes.

Hourly observations were compared against corresponding hourly predictions from the most recent model run. Modeled and observed winds were compared by interpolating the modeled surface wind variables to the observed surface sensor locations at each site. The 10-m winds from NAM, HRRR, WRF-UW, and WRF-NARR forecasts were interpolated to sensor locations, using bilinear interpolation in the horizontal dimension and a log profile in the vertical dimension. A 3-D interpolation scheme was used to interpolate WindNinja winds to the sensor locations. This 3-D interpolation was possible because the WindNinja domains had layers above and below the surface sensor height (3.043 m AGL). A 3-D interpolation scheme was not possible for NWP domains since there were not any layers below the surface sensor height.

Model performance was quantified in terms of the mean bias, root-mean-square error (rmse), and standard deviation of the error (sde):

$$\overline{\varphi'} = \frac{1}{N}\sum_{i=1}^{N} \varphi'$$

$$\text{rmse} = \left[\frac{1}{N-1}\sum_{i=1}^{N}(\varphi_i')^2\right]^{1/2}$$

$$\text{sde} = \left[\frac{1}{N-1}\sum_{i=1}^{N}(\varphi_i' - \overline{\varphi'})^2\right]^{1/2}$$

where φ' is the difference between simulated and observed variables and N is the number of observations.

IV. Key Findings

Objective 1

Surface winds on and around BSB were completely decoupled from large-scale flows during upslope and downslope flow regimes, except for at the highest elevation ridgetop sensors. These ridgetop locations at BSB tended to correlate better with gradient-level winds than with the local diurnal surface flows. Surface winds in SRC were decoupled from large-scale flows except during periods of surface pressure-driven easterly winds that enhanced downriver flows.

Wind speeds increased with distance upslope during the upslope regime at BSB, but generally decreased with distance upslope at SRC. Wind speed did not have a simple, consistent trend with position on the slope during the downslope regime at BSB, but generally increased with distance upslope at SRC. We did not observe a convective mixing regime at SRC, only a transition from upslope to thermally-driven upriver flow.

The highest speeds measured at BSB occurred during the passage of frontal systems which generated strong southwesterly flows and during infrequent strong northwesterly flow events presumably generated through convergence zone dynamics, thunderstorm outflows, or surface pressure gradients. Ridgetop winds were often twice as high as surface wind speeds measured on the surrounding SRP. The highest speeds measured at SRC occurred during late morning hours and were from easterly flows presumably produced by surface pressure gradients induced by formation of a thermal trough over the Columbia Plateau to the NW and high pressure to the east. The highest wind speeds during these pressure-driven easterly flow events were measured at the mid to high elevation sensors.

These results have important implications for modeling near-surface winds in complex terrain. Under periods of weak synoptic forcing, surface winds tended to be decoupled from large-scale flows due to effects of local surface heating and cooling, and under periods of strong synoptic forcing, variability in surface winds was sufficiently large due to terrain-induced mechanical effects (speed-up over ridges and decreased speeds on leeward sides of terrain obstacles) that a large-scale mean flow would not be representative of surface winds at most locations on or within the terrain feature. These findings suggest that traditional operational weather model (i.e., with numerical grid resolutions of around 4 km or larger) wind predictions are not likely to be good predictors of local near-surface winds at sub-grid scales in complex terrain. The findings from this work along with the additional archived data and available mesonet data at BSB should provide guidance for future development and evaluation of high-resolution wind models and integrated parameterizations, such as for simulating diurnal slope flows and non-neutral atmospheric stability effects.

Objective 2

Wind speed predictions at BSB were improved for all NWP models by downscaling with WindNinja. The biggest improvements occurred during synoptically-driven events when observed wind speeds were greater than 10 m s^{-1}. Downscaled NAM (12 km resolution) wind speeds were as accurate as downscaled WRF-UW (4 km resolution) and HRRR (3 km resolution) wind speeds at BSB. The highly complex terrain surrounding the SRC site induced large-scale features into the flow that required high resolution NWP simulations to resolve in order to appropriately describe the mean flow field and provide adequate initial conditions for the WindNinja simulations. There was no improvement in downscaled wind speeds at SRC, although predicted wind directions improved for all NWP models and flow regimes.

Wind directions improved at both SRC and BSB during upslope and downslope flow regimes, due at least in part to the diurnal slope flow algorithm in WindNinja. There were mixed results at BSB and WindNinja consistently over-predicted wind speeds during the upslope and downslope flow regimes at SRC. This suggests a potential limitation of the existing parameterizations within the diurnal slope flow algorithm used in WindNinja and should be further investigated.

Results indicate that NWP model wind forecasts can be improved in complex terrain at least in some cases through dynamic downscaling via a mass-conserving wind model. These improvements should propagate on to more realistic predictions from fire spread and behavior applications which are highly sensitive to surface wind fields.

Objective 3

We added-built in support for obtaining gridded digital elevation models (DEMs) and gridded vegetation data (multi-band Landscape raster files) from online data sources. These data can now be obtained via a simple Google Maps interface in WindNinja. This, along with the previously built-in support for obtaining NWP forecasts, makes it very simple for users to obtain all necessary data to do a WindNinja simulation. Use of these built-in data fetchers requires no technical expertise by the user and has essentially no impact on the simulation time.

A non-neutral atmospheric stability algorithm has been incorporated into WindNinja. This algorithm should improve wind predictions when the stability of the atmosphere is far from neutral, especially under stable conditions (e.g., calm nighttime conditions) when vertical motion is suppressed, causing flow to accelerate around terrain obstacles. Data collected from BSB and SRC are being used to evaluate this non-neutral stability parameterization under different types of stability conditions.

One of the findings from the model evaluations work was that WindNinja often over-predicted wind speeds during the upslope and downslope flow regimes, particularly at SRC. This indicates a potential limitation of the existing parameterizations within the diurnal slope flow algorithm used in WindNinja. We are now conducting evaluations of the diurnal slope flow algorithm in WindNinja using data collected from BSB and SRC. These evaluations should provide guidance for modifying the parameters used in the slope flow algorithm.

Objective 4

Results from the model evaluations showed that routine NWP surface wind forecasts can, at least in some cases, be improved by downscaling with WindNinja in regions of complex terrain. As long as the mean flow for the domain is captured by the NWP model, downscaling with WindNinja improves predictions by incorporating the mechanical and, to some extent, the thermal effects of the sub-grid terrain on the flow field. WindNinja currently has built-in support for initialization with four operational NWP forecasts: the North American Model (NAM), National Digital Forecast Database (NDFD), Global Forecast System (GFS), and Rapid Refresh (RAP). We are in the process of including built-in support for all forecasts provided by the NOAA Operational Model Archive and Distribution System (NOMADS); this will increase the number of NWP models available in WindNinja and hopefully offer better regional forecasts for many locations.

V. Management Implications

Observations from the BSB and SRC field campaigns showed that local near-surface flows are often decoupled from larger-scale mean flows. Under periods of weak synoptic forcing, surface winds tended to be decoupled from large-scale flows due to effects of local surface heating and cooling, and under periods of strong synoptic forcing, variability in surface winds was sufficiently large due to terrain-induced mechanical effects (speed-up over ridges and decreased speeds on leeward sides of terrain obstacles) that a large-scale mean flow would not be representative of surface winds at most locations on or within the terrain feature. This suggests that traditional operational NWP model wind predictions are not likely to be good predictors of local near-surface winds at sub-grid scales in complex terrain.

Model evaluations with observed data from BSB and SRC showed that, in at least some cases, NWP model winds can be improved by downscaling with WindNinja. WindNinja appears to improve surface wind predictions as long as the NWP model reasonably captures the large-scale mean flow within the domain. Improvements in wind speed from downscaling were largest during high wind events. Improvements in wind direction were largest during periods of calm conditions, when local solar heating and cooling had a large impact on the local flow field. These results indicate that WindNinja could be used to improve surface wind predictions from NWP models in complex terrain under a number of meteorological conditions.

WindNinja users should note that large-scale effects, such as pressure differences, land-sea breezes, etc. are not accounted for in WindNinja, and therefore, these effects must be incorporated into the NWP model winds used to initialize the WindNinja model. In regions of highly complex terrain, such as the SRC site, a very high resolution NWP model forecast may be necessary to provide an adequate wind field for downscaling with WindNinja. In other areas, such as the BSB site, relatively coarse NWP model winds may be sufficient for providing the initial wind field for downscaling with WindNinja.

VI. Relationship to Ongoing Work

There are a number of ongoing research efforts related to this work:

- **Incorporation of a momentum solver:** We are in the process of incorporating an optional momentum solver into the WindNinja model. The momentum solver is based on the open source computational fluid dynamics package, OpenFOAM. Incorporation of a momentum solver could improve wind predictions in some cases, for example, in areas of flow separation, such as on the lee side of terrain features. Data from BSB and SRC will be used to evaluate determine the improvements, if any, from incorporating the momentum solver.
- **Evaluating and improving thermal parameterizations**: Data from BSB and SRC are being used to evaluate the diurnal slope flow and non-neutral stability sub-models in WindNinja. We have observed data covering a range of meteorological conditions at each site which should allow us to detect and correct deficiencies in the thermal parameterizations used in the slope flow and stability algorithms.
- **Built-in support for additional NWP models for initialization:** We are in the process of adding built-in support for all forecasts provided by the NOAA Operational Model Archive and Distribution System (NOMADS); this will increase the number of NWP models available in WindNinja and hopefully offer better regional forecasts for many locations.
- **Post-fire wind erosion:** We have added a PM10 (particles <10 μm in diameter) emissions algorithm for post-fire soils in WindNinja. The emissions algorithm predicts gridded PM10 emissions as a function of friction velocity (a measure of shear stress at the surface calculated by WindNinja from the near-surface wind speed gradient), the threshold friction velocity required for particle movement (dependent on the soil), and PM10 release rate (dependent on the soil). Preliminary values for threshold friction velocity and PM10 release rate were determined from field measurements (Wagenbrenner et al., 2013). We are using WindNinja-Dust for a current

project to predict PM10 emissions from two burn scars in sagebrush ecosystems, one in southeast Idaho in 2010 and one in southeast Oregon in 2012, which produced enough dust to raise air quality issues in the months following the fires. These emissions will then be fed into a regional scale transport and dispersion model to investigate downwind impacts. Results from this work will be presented at the International Conference on Atmospheric Dust in Taranto, Italy, June 1-6 2014.

VII. Future Work

- **Additional observations in complex terrain**: Data collected from the three field campaigns conducted during this study have expanded the archive of available data for evaluating high resolution wind models; however, additional data are necessary to build an inventory of observations representing a range of complex terrain types, vegetation cover, and meteorological conditions, to more fully evaluate these types of models.
- **Terrain complexity indices**: It could be useful to quantify model performance as a function of sub-grid terrain complexity indices. This sort of metric could perhaps be used by fire managers to provide guidance on the type of NWP model forecast (e.g., the horizontal resolution) they should aim for in a given location, or at least provide some measure of confidence in a given forecast for a particular location. The terrain complexity index could be easily calculated by WindNinja based on the digital elevation model and, if we find that a relationship exists between model performance and sub-grid terrain complexity, would offer a quantitative measure for assigning confidence to surface wind forecasts.
- **PREF data**: We will analyze the data collected from PREF to look at effects of tall forest canopies on near surface winds. This data will be useful for evaluating a planned canopy flow model in WindNinja.
- **Momentum solver evaluations**: Data collected from BSB and SRC will be used to evaluate the newly incorporated momentum solver in WindNinja.
- **Hill-wake parameterization**: Work could be done to develop a parameterized hill-wake model based on simulations from the momentum solver. If this parameterization works, users would get the speed of WindNinja and improved accuracy in some locations from the parameterized momentum effects.

VIII. Deliverables crosswalk table.

Proposed	Delivered	Status
Peer-reviewed article	Technical article on field measurements	In review
Peer-reviewed article	Technical article on model evaluation	In preparation (90% complete)
Workshops and Technical Conferences	Presentations at Ag & Forest Meteorology AMS Conferences and other appropriate workshops	Completed
Compiled meteorological data base	On-line data base	Completed

Websites

WindNinja development site: https://collab.firelab.org/software/projects/windninja/

Access to archived data: https://collab.firelab.org/software/projects/wind-obs/wiki

Online interface to observed data: http://forest.moscowfsl.wsu.edu:3838/shinyWindToolsTest/

Publications

Butler, B.W., Wagenbrenner, N.S., Forthofer, J.M., Lamb, B.K., Shannon, K.S., Finn D., Eckman, R.M., Clawson, K., Bradshaw, L., Sopko, P., Beard, S., Jimenez, D., Wold, C., Vosburgh, M., In Review. High resolution observations of the near-surface wind field over an isolated mountain and in a steep river canyon. Submitted to Atmos. Chem. Phys.

Wagenbrenner, N.S., Lamb, B.K., Forthofer, J.M., Shannon, K.S., Butler, B.W., In preparation. Downscaling surface wind predictions from numerical weather prediction models in complex terrain with a mass-consistent wind model. To be submitted to J. Appl. Meteorol. Climatol.

Technical Presentations and Workshops

Forthofer, J.M., Shannon, K.S., Wagenbrenner, N.S., Butler, B.W., Posey, C., 2014. Modeling surface winds with WindNinja. Incident Meteorologist Virtual Workshop. April 15, 2014.

Wagenbrenner, N.S., Forthofer, J.M., Lamb, B.K., Shannon, K.S., Butler, B.W., 2013. Observations of surface winds over an isolated mountain and in a steep river canyon. Northwest Regional Modeling Consortium. December 3, 2013. Seattle, WA.

Wagenbrenner, N.S., 2013. Evaluation and development of a wind model for wildfire applications in complex terrain. Research seminar. Department of Biological Systems Engineering, Washington State University. November 15, 2013. Pullman, WA.

Forthofer, J.M., Wagenbrenner, N.S., Butler, B.W., Shannon, K.S., 2013. High speed morning winds in the Salmon River Canyon and the potential impact on wildland fire behavior. Great Divide Workshop. National Weather Service. October 23, 2013. Missoula, MT.

Forthofer, J.M., Shannon, K.S., Butler, B.W., Wagenbrenner, N.S., Posey, C., 2013. Wind simulations using WindNinja. Missoula Fire Sciences Laboratory Seminar Series. May 16, 2013. Missoula, MT.

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Wagenbrenner, N.S., Lamb, B.K., Yedinak, K., Forthofer, J.M., Shannon, K.S., Butler, B.W., Finn, D., 2012. Development of high-resolution wind simulation tools to improve fire weather forecasts. American Meteorological Society Annual Meeting. January 2012. New Orleans, LA.

Wagenbrenner, N.S., Lamb, B.K., Forthofer, J.M., Shannon, K.S., Butler, B.W., Robichaud, P.R., Foltz, R.B., Germino. M., 2011. Wind erosion of soil burned by wildfire: measurements and modeling efforts. Research seminar. Polytechnic University of Milan. May 3, 2011. Milan, Italy.

Wagenbrenner, N.S., Lamb, B.K., Yedinak, K., O'Keefe, P., Allwine, G., Forthofer, J.M., Shannon, K.S., Butler, B.W., Robichaud, P.R., Finn, D., 2011. Development of high-resolution wind simulation tools to improve fire weather forecasts. European Geosciences Union Annual Meeting. April 3-8, 2011. Vienna, Austria.

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