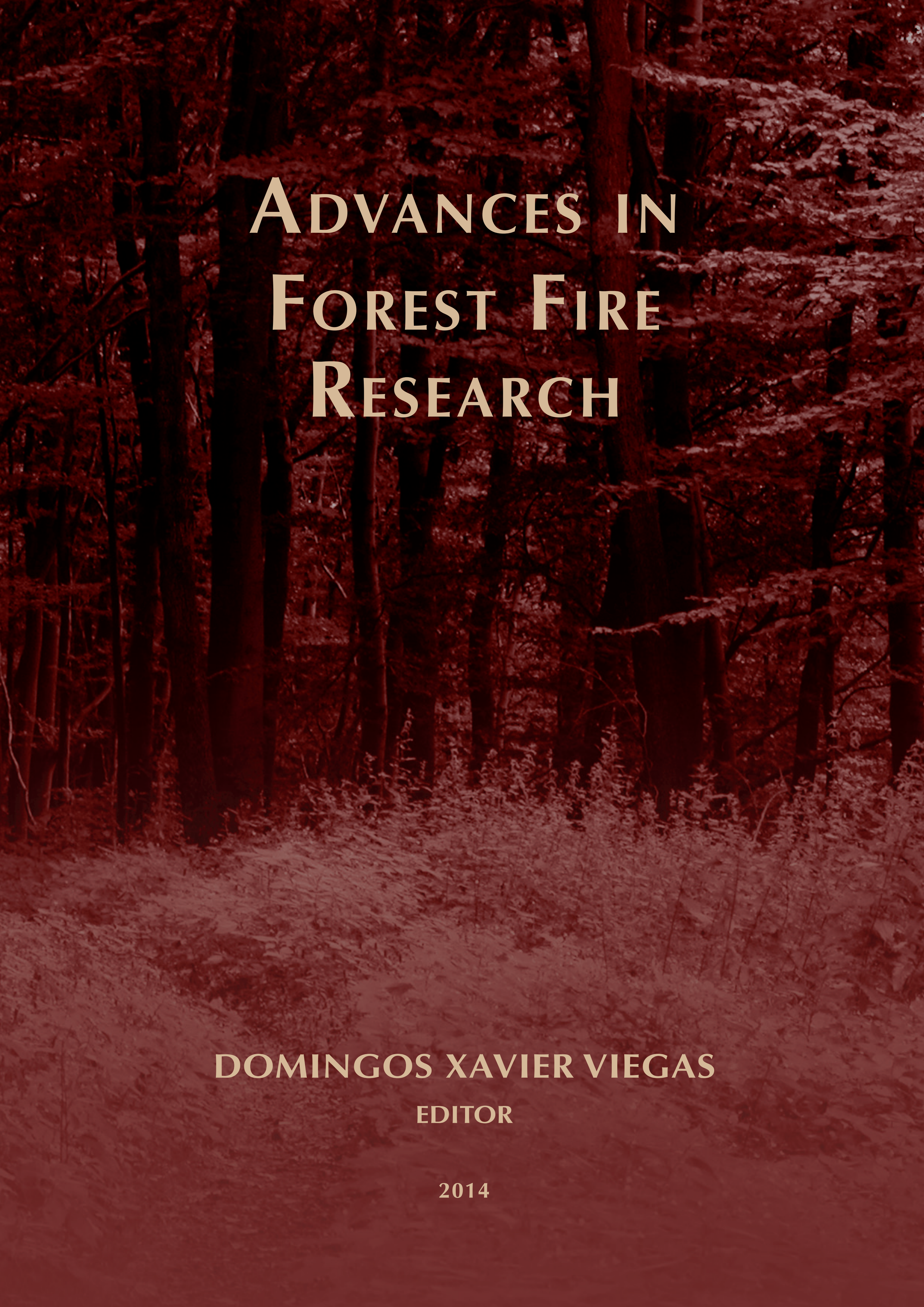

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An update on the WindNinja surface wind modeling tool

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Abstract
The WindNinja surface wind modeling tool is being used throughout the world to support wildland fire management. It continues to be updated and improved. Recent improvements include the capability to initialize simulations based on meso-scale weather forecast data or direct observations, an improved tool for accessing elevation data, and access to a momentum solver. This paper describes current status of the tool and planned enhancements.

Keywords*: Fire behavior, prescribed fire, fire modeling*

1. Introduction

The temporal and spatial variability in near-surface winds is one of the primary environmental factors influencing wildland fire behavior (Rothermel 1972; Albini 1981; Williams 1982; Linn *et al.* 2007). Historically, fire managers have relied on expert judgment, point measurements, or weather forecasts to estimate local winds (Butler *et al.* 1998; USDA Forest Service and USDI Bureau of Land Management 2002). These methods can lead to large errors in estimated wind speed and direction and subsequently to corresponding uncertainty in fire growth simulations, especially in complex terrain. Others have identified the need for computationally efficient decision support systems for applications involving hazardous chemical or biological releases into the atmosphere and battlefield tactical situations (Davis *et al.* 1984; Homicz 2002; Ling and Shuming 2003; Vaucher and Luces 2011). In order to be useful as a decision support tool for operational fire management, the model must meet several constraints: 1) minimum level of required technical expertise (i.e. not necessarily extensively trained in meteorology); 2) short computational time (i.e. less than 1 hour); 3) minimum computing hardware (i.e. can be run on low cost laptop computers), 4) fine spatial resolution (~ 100 m) of winds at 3 to 10 m above ground level. This paper provides an update on a high resolution surface wind model called WindNinja which meets these constraints (Forthofer *et al.* in press).
WindNinja is a mass-conserving diagnostic model designed for simulating fine-scale, terrain-driven winds. It is widely used in North America to simulate winds in support of wildland fire management. The model seeks to minimize the change from an initial wind field while conserving mass. Details regarding the technical foundation of the model are provided in Forthofer *et al*. (in press). The model can be run via a simple graphical user interface (Figure 1) or a command line interface. Required inputs include a digital elevation model, an initial wind field, and vegetation information. Model outputs are gridded surface or volume wind fields in the following formats: .kmz for viewing in Google Earth, .shp and .asc for viewing in GIS applications, .atm for input to FARSITE and FlamMap fire spread models, and .vtk for viewing in 3-D visualization applications. WindNinja is typically run on domain sizes of up to 50 x 50 km and resolutions on the order of 100 m. Typical simulation times are around 10-30 seconds.
Here we outline the current status of the model with an overview of (1) new features including a diurnal slope flow parameterization, initialization using numerical weather model forecast data, a non-neutral atmospheric stability parameterization, and automated download of terrain data; (2) model validation work with newly collected field observations; and (3) ongoing work including incorporation of an

optional momentum solver, a new GeoPDF output format option, and development of a WindNinja mobile application.

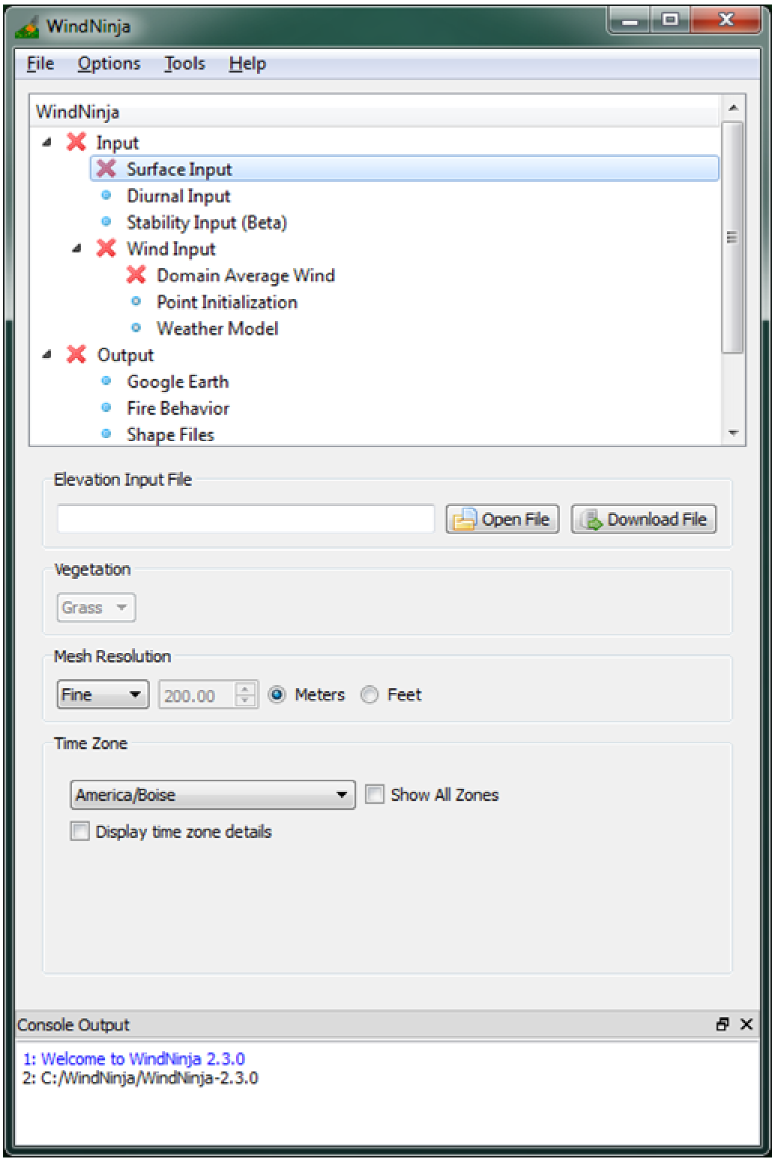

Figure 1. WindNinja graphical user interface.

2. New features

Diurnal slope flow

An optional diurnal slope flow parameterization has been added to the WindNinja model to simulate local thermally-driven upslope and downslope flows (Forthofer *et al.* 2009). The diurnal slope flow model simulates slope flows induced by local surface heating and cooling. These types of slope flows are most important when gradient wind speeds are low and thermally-induced effects outweigh the mechanically-induced effects on the flow.

The technical foundation of the diurnal slope flow model is described in (Forthofer *et al.* 2009). It includes a micrometeorological model based on (Scire and Robe 1997; Scire *et al.* 2000) which estimates atmospheric stability, surface heat and momentum fluxes, and boundary layer height.

Incident solar radiation is computed within each surface cell using the algorithm from the National Renewable Energy Laboratory (Rymes 2011) and a custom terrain shadow computation. The slope flow model is a one-dimensional model of buoyancy-driven flow along a slope. The magnitude of the slope flow is calculated at each surface grid cell as a function of acceleration distance (distance to ridgetop or valley bottom), percent slope, surface and entrainment drag parameters, and surface sensible heat flux. The direction of slope flow within each cell is exactly upslope or downslope and the depth of the slope flow is assumed to be 5% of the elevation difference to the ridge or valley. Once calculated, the slope flow component in each cell is added to the initial wind field and then the WindNinja solver is run to generate the final mass-conserving flow field.
Since incident solar radiation must be computed, use of the slope flow model requires that the following additional input parameters be specified: date, time, cloud cover, and air temperature. If the simulation is initialized with a weather model forecast, this information is obtained automatically from the weather model data, otherwise it must be supplied. Validation of the diurnal slope flow model with field observations is described below.

Weather model initialization

WindNinja allows initialization with a number of weather model forecasts. Numerical weather models compute gridded predictions of *u*, *v*, *w*, pressure, moisture, and heat on 3-D computational domains. They include sophisticated schemes for boundary-layer dynamics, cloud microphysics, and land-surface interactions. They typically simulate large areas (regional to continental scale), employing computational grids with horizontal resolutions of 4 km or larger. Because of the large computational expense required to simulate detailed physical processes over such large areas, it is not possible to run these types of models at a fine enough resolution to capture local terrain effects on the flow. In contrast, WindNinja is designed to simulate fine-scale winds that are dominated by mechanical terrain modification and local slope flows induced by local surface heating and cooling. Weather model forecasts linked with higher-resolution wind models can produce more accurate surface wind forecasts (Beaucage *et al.* 2014), as synoptic-scale forces and planetary boundary layer processes are resolved by the weather model to generate an initial wind field which is then downscaled by the higher resolution wind model that better resolves individual terrain features. The effect of downscaling weather model surface wind predictions with WindNinja is discussed below.
WindNinja includes built-in support for downloading and initialization with the following forecasts provided by the National Centers for Environmental Prediction: National Digital Forecast Database (NDFD), North American Mesoscale Model (NAM), Rapid Refresh Model (RAP), and Global Forecast System (GFS) (Table 1). Additionally, limited support has been added for the following forecasts via the command line interface: Weather Research and Forecasting (WRF-ARW) (netCDF format), historical NAM (GRIB2 format), and High Resolution Rapid Refresh (HRRR) (GRIB2 format). WindNinja only supports reading and initialization with these additional models, and does not offer download support, so the user must obtain these forecasts from another source.
WindNinja uses the 10-m wind speed and direction, cloud cover, and 2-m temperature from the weather model forecast. Only this subset of variables is downloaded from the full forecast for each output time step so the data transfer is very fast (typically just a few seconds). WindNinja performs an individual WindNinja simulation for every output time step in the weather model forecast. During each WindNinja run, the coarse-scale weather model forecast data is interpolated to the finer-scale WindNinja computational grid. Diurnal winds are added if the diurnal slope flow algorithm is enabled to produce the final initial wind field. Finally, the WindNinja solver is run on this initial wind field to produce a final flow solution that conserves mass.

Table 1. Weather model forecasts available for download in WindNinja

Model Name in WindNinja	Description	Horizontal Resolution	Forecast Duration	Temporal Resolution	Update Frequency
NCEP-NDFD-5km	National Digital Forecast Database	5 km	168 hours (7 days)	Every 6 hours	12 and 18 UTC
NCEP-NAM-12km-SURFACE	North American Mesoscale Model (lower 48 domain)	12 km	84 hours (3.5 days)	Every 3 hours	00, 06, 12, and 18 UTC
NCEP-NAM-Alaska-11km-SURFACE	North American Mesoscale Model (Alaska domain)	11 km	84 hours (3.5 days)	Every 3 hours	00, 06, 12, and 18 UTC
NCEP-RAP-13km-SURFACE	Rapid Refresh Model	13 km	18 hours (0.75 days)	Every 1 hour	hourly
NCEP-GFS-GLOBAL-0_5deg-SURFACE	Global Forecast System	0.5°	168 hours (7 days)	Every 3 hours	00, 06, 12, and 18 UTC

Non-neutral atmospheric stability

Atmospheric stability is a measure of the resistance of the atmosphere to vertical motion due to variations in air density with height above the ground. Under stable atmospheric conditions, vertical motion is inhibited and the flow will tend to flow around, rather than up and over terrain obstacles. Under unstable atmospheric conditions, vertical motion is favored and flow will tend to more easily move up and over terrain obstacles. Atmospheric stability is a dynamic phenomenon and it can vary spatially within a given domain.

The native WindNinja solver assumes a neutral atmosphere (vertical motions are neither suppressed nor favored). An optional atmospheric stability model has been incorporated into WindNinja for simulating non-neutral atmospheric conditions. The model estimates atmospheric stability from the surface heat flux calculated using methods from the diurnal slope flow model. Currently, a single stability value is assigned to the full vertical profile (from the ground surface to the top of the model domain) for each surface grid cell. Future improvements to the stability model will likely use additional information to more fully describe the state of the atmosphere. Because of this, the stability model is considered a beta test version at this time. Use of the stability model requires the following additional input parameters for calculation of the surface heat flux: cloud cover, date, and time. If the simulation is initialized with a weather model forecast, this information is obtained automatically from the weather model data, otherwise it must be supplied.

Elevation file grabber

An option to download a digital elevation model (DEM) has been added to WindNinja. This feature is referred to as the “elevation file grabber.” The elevation file grabber uses a Google Maps interface which can be launched either from the graphical user interface or the command line interface (Figure 2). The elevation file grabber allows the user to swoop out an area of interest on the interactive map. After selection of the area, a transparent red box will be drawn on the map indicating the defined area (Figure 2). This box can be enlarged or shrunk by dragging the sides and corners of the box or it can be translocated by dragging the center icon. There are three data sources from which DEM data can be downloaded from: US SRTM, WORLD SRTM, and WORLD GMTED (Table 2). Once the area of interest has been defined and the DEM data source has been selected, the DEM can be downloaded by WindNinja from a United States Geological Survey (USGS) server.

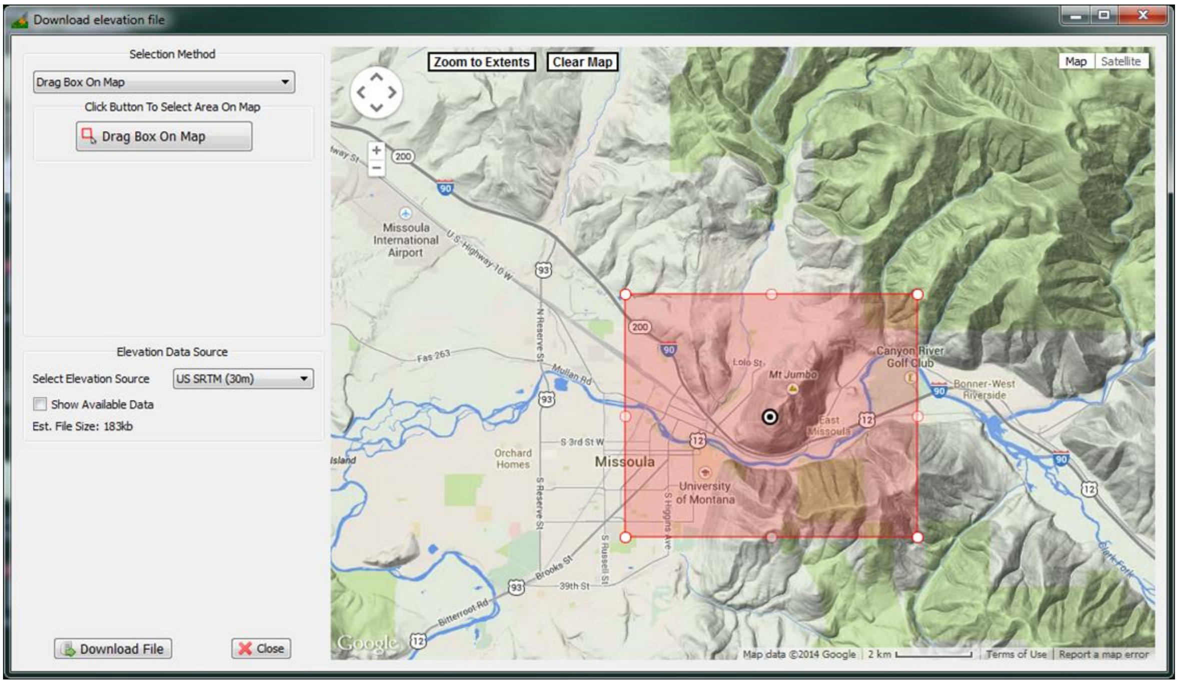

Figure 2. Elevation file grabber.

Table 2. Digital elevation model data sources

Data source	Resolution	Spatial extent	Description
US SRTM	30 m	Contiguous US, Hawaii, Puerto Rico, southern Alaksa	Data from the Shuttle Radar Tomography Mission (SRTM)
WORLD SRTM	90 m	-60° to +60°	Data from the Shuttle Radar Tomography Mission (SRTM)
WORL GMTED	250 m	-60° to +85	Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010)

3. Model validation

There is little observational data available at appropriate spatial scales for evaluating high resolution wind models like WindNinja. To address this issue and facilitate validation of high-resolution wind models, we conducted a series of intensive field campaigns to collect high-resolution near-surface wind observations from four different field locations in complex terrain. Data from two of these field campaigns has been published (Butler *et al.* 2014) and used to evaluate use of WindNinja for downscaling numerical weather model forecast winds in complex terrain (Wagenbrenner, in preparation). Results from this work demonstrate that WindNinja can improve near-surface wind forecasts in many cases as long as the large-scale flow in the domain is adequately captured by the weather model. The biggest improvements in speed predictions occurred during periods of high winds and the biggest improvements in direction predictions occurred under periods of upslope and downslope flow. The largest errors in WindNinja-predicted wind speed and direction tend to occur on the lee side of terrain obstacles (Forthofer *et al*., in press; Wagenbrenner *et al*., in preparation). We found that the diurnal slope flow algorithm helped to correctly orient winds during periods of upslope and downslope flows, but that the strength of the modeled slope flows tended to be weaker than the observed slope flows (Wagenbrenner *et al*. in preparation). This suggests that additional work could be done to improve parameterizations in the diurnal slope flow algorithm.

4. Ongoing work

Ongoing work includes incorporation of an optional momentum solver, design of an application for WindNinja simulations on mobile devices, and an additional GeoPDF output format option. Incorporation of the momentum solver should improve wind predictions on the lee side of terrain obstacles, in at least some cases. The new GeoPDF output format will all users to view gridded output surface winds on a map saved locally on their computer or mobile device. This will allow viewing of the output on a dynamic map without an internet connection or cell phone coverage and is expected to be useful to users in remote field locations. The mobile application will allow initiation of a WindNinja simulation from a mobile device. This should improve usability in field settings where use of computers or laptops may not be convenient.

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