EVALUATION AND DEVELOPMENT OF A HIGH RESOLUTION WIND
MODEL FOR WILDFIRE APPLICATIONS IN COMPLEX TERRAIN

By

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EVALUATION AND DEVELOPMENT OF A HIGH RESOLUTION WIND MODEL FOR WILDFIRE APPLICATIONS IN COMPLEX TERRAIN

Abstract

by Natalie Suzanne Wagenbrenner, Ph.D.
Washington State University
December 2013

Chairs: Brian K. Lamb and Joan Q. Wu

Accurate modeling of near-surface winds is important for wildfire applications, including wildfire behavior and spread as well as post-fire processes, including wind-driven dust and ash emissions from burned soils. The work presented in this dissertation investigates a high-resolution wind model for use in wildfire applications in complex terrain and includes (1) an observational field study to collect high resolution surface wind data from two types of complex terrain features; (2) use of these observed data to evaluate a suite of Numerical Weather Prediction (NWP) model for near-surface wind predictions and dynamical downscaling of those predictions with a high resolution wind model; and (3) field quantification of wind erosion from soils burned by wildfire. Unique flow features, including upslope, downslope, and synoptically-driven flow events were presented for an isolated mountain and a steep river canyon. Evaluations with these observed datasets indicated that NWP surface winds can be improved in complex terrain via dynamic downscaling with a high resolution wind model, WindNinja, so long as the average approach flow to the area of interest can be reasonably defined (i.e., the initial wind field must be appropriately defined). The biggest improvements occurred during periods of synoptically-driven events when observed winds speeds exceeded 10 m s$^{-1}$. Results
from the post-fire field campaign demonstrated that post-fire landscapes can be significant sources of particulates and that dust emissions can persist for up to a year post-fire. Data collected during this study represents the first real-time measurements of PM$_{10}$ fluxes from a burned landscape. These data will be useful in evaluating windblown dust emissions algorithms applied to burned landscapes.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>ACKNOWLEDGEMENTS</th>
<th>iii</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>x</td>
</tr>
<tr>
<td>ATTRIBUTION</td>
<td>xiv</td>
</tr>
</tbody>
</table>

## CHAPTER

1. INTRODUCTION ................................................................. 1

2. HIGH RESOLUTION OBSERVATIONS OF THE NEAR-SURFACE WIND FIELD ON AN ISOLATED MOUNTAIN AND IN A STEEP RIVER CANYON ...... 5
   2.1. Introduction ................................................................... 6
   2.2. Instrumentation ............................................................. 8
   2.3. Site Descriptions ........................................................... 13
      2.3.1. Big Southern Butte (BSB) ......................................... 13
      2.3.2. Salmon River Canyon (SRC) ...................................... 15
   2.4. Analysis Methods and Terminology .................................. 15
      2.4.1. Partitioning surface data into flow regimes ................ 16
      2.4.2. Data averaging ....................................................... 18
   2.5. Results and Discussion .................................................. 19
      2.5.1. BSB ..................................................................... 20
         2.5.1.1. Diurnal winds: upslope, afternoon, and downslope regimes ........................................... 20
3.4.a.ii. Upslope, downslope, and synoptically-forced flows……..66

3.4.b. SRC..................................................................................................................67

3.4.b.i. 5-day simulations............................................................................................67

3.4.b.ii. Upslope, downslope, and synoptically-forced flows……..75

3.5. Conclusions............................................................................................................76

3.6. Acknowledgements..............................................................................................77

4. WIND EROSION FROM A SAGEBRUSH STEPPE BURNED BY WILDFIRE: MEASUREMENTS OF PM10 AND TOTAL HORIZONTAL SEDIMENT FLUX........................................................................81

4.1 Introduction............................................................................................................83

4.2 Methods..................................................................................................................84

4.2.1. Site Description..................................................................................................84

4.2.2 Measurements....................................................................................................89

4.3 Results....................................................................................................................95

4.3.1 Specific events....................................................................................................101

4.4 Discussion...............................................................................................................104

4.5 Conclusions..........................................................................................................110

4.6. Acknowledgements............................................................................................112

5. SUMMARY AND FUTURE WORK...........................................................................117
LIST OF TABLES

Chapter 2

1. Sonic anemometer and vertical profiling sensor details.....................................................10

2. Radiosonde launches at BSB and SRC. Times are LT .......................................................11

3. Measured wind speeds (m s\(^{-1}\)) during upslope, downslope, and convective mixing regimes at BigSouthern Butte (BSB) and Salmon River Canyon (SRC). Decoupled ridgetop locations (sensors R26, R35, TSW7, and R15) were omitted from BSB averaged; speeds in parentheses include ridgetop sensors..................................................................................................................22

Chapter 3

1. Model specifications. When values differ between field sites, the values for Salmon River Canyon are in parentheses.................................................................52

2. Model mean bias, root-mean-square error (rmse), and standard deviation of errors (sde) for surface wind speeds and directions at BSB...................................................65

3. Model mean bias, root-mean-square error (rmse), and standard deviation of errors (sde) for surface wind speeds and directions at SRC.........................................................74

Chapter 4

1. Calculated PM\textsubscript{10} vertical fluxes, horizontal sediment fluxes, and ratios of PM\textsubscript{10} vertical flux to horizontal sediment flux for four wind erosion events.................................................100

2. Horizontal sediment fluxes measured in this study compared to values reported in the literature..........................................................................................................................106

3. PM\textsubscript{10} ambient concentrations and vertical fluxes measured in this study compared to values reported in the literature.................................................................107
LIST OF FIGURES

Chapter 2

1. Sensor layouts at the Salmon River Canyon (a) and Big Southern Butte (b, c). Black circles indicate surface sensors. Red diamonds indicate sonic anemometers and vertical profiling sensors. .................................................................12

2. Snake River Plain and prominent drainages surrounding the BSB study site. .................14

3. Observed hourly wind speeds for R2 at BSB and NM1 at SRC. The horizontal line indicates the threshold speed chosen to partition synoptically driven events from diurnal events ……18

4. Upslope (1100 LT), afternoon (1600 LT), and downslope (0000 LT) flow regimes at BSB during periods of weak synoptic flow between June-September 2010. Vectors represent the average hourly flow at a given sensor. Vectors are centered on sensor locations. Periods of strong synoptic forcing were removed prior to averaging. Upper strip is zoomed in on the butte. Lower strip is zoomed out to show entire study area. .................................................................21

5. Average wind speeds for sensors at three slope locations (low, mid, and high) along three transects during the (a) upslope (1100 LT) and (b) downslope (0000 LT) flow regimes at BSB. ...............................................................................................23

6. Contour plots of hourly wind frequencies and corresponding wind speeds for a transect on the southwest slope of Big Southern Butte (left panels) and a transect on the northeast slope of Big Southern Butte (right panels). Panels are ordered from higher elevation sensors (top panels) to lower elevation sensors (bottom panels). Periods of synoptic forcing were removed from this data. ...............................................................................................24

7. Contour plots of hourly wind frequencies and corresponding wind speeds for four ridgetop locations at Big Southern Butte. Periods of strong synoptic forcing were removed from this data. ...............................................................................................27

8. Characteristic synoptically-driven regime events during the passage of a frontal system (1800 LT) and during synoptically-enhanced downvalley flow on the Snake River Plain (2300 LT) at BSB during June–September 2010. Vectors represent the average hourly flow at a given sensor. Periods of weak synoptic forcing were removed prior to averaging. Lower strip is zoomed out to show entire study area. .........................................................................................29

9. Upslope (1100 LT), afternoon (1600 LT), and downslope (0000 LT) regimes at SRC during periods of weak synoptic flow between July–September 2011. Vectors represent the average hourly flow at a given sensor. Periods of strong synoptic forcing were removed prior to averaging. .........................................................................................31
10. Average wind speeds for sensors at three slope locations (low, mid, and high) along five transects during three hours of the upslope (top panels) and downslope (bottom panels) flow regimes at SRC. Blue and red lines are transects on the south and north side of the river, respectively…………………………………………………………………………………………………32

11. Average wind speeds for sensors at three slope locations (low, mid, and high) along five transects during the afternoon flow regime (1700) at SRC. Blue and red lines are transects on the south and north side of the river, respectively………………………………………………………………………………………………34

12. Contour plots of hourly wind frequencies and corresponding wind speeds for the NM transect at SRC. NM1 is near the ridgetop. NM4 is near the canyon bottom. All data were used….36

13. Characteristic synoptically driven upvalley flow (1500 LT) and downvalley flow (1100 LT) at SRC during July-September 2011. Vectors represent the average hourly flow at a given sensor. Periods of weak synoptic forcing were removed prior to averaging………………..37

14. Synoptic-scale pressure conditions conducive to enhanced easterly flow (left) and typical diurnal flow scenarios (right) at SRC. Top panel isobars are surface level pressures. Bottom panel isobars are 500 mb height pressures. (National Center for Environmental Prediction)……………………………………………………………………………………………………..39

15. Average wind speeds for sensors at three slope locations (low, mid, and high) along five transects during the synoptically driven upvalley (left) and synoptically driven downvalley (right) flow regimes at SRC. Blue and red lines are transects on the south and north side of the river, respectively………………………………………………………………………………………………40

Chapter 3

1. Terrain representation in WindNinja, WRF-NARR, HRRR, and WRF-UW for the BSB (top panels) and SRC (bottom panels). Surface sensor locations are shown as crosses in the WindNinja image. Scale bars are in km. NAM terrain is represented by just four cells for BSB and one cell for SRC and is not shown here………………………………………..58

2. Observed vs. predicted wind speeds for the 5-day evaluation periods at BSB (left) and SRC (right). Dashed black line is the 1:1 line. Colored lines are loess (locally weighted scatterplot smoothing) regressions; dashed lines are NWP models and solid lines are NWP forecasts downscaled with WindNinja. Shading indicates 95% confidence intervals…………………..60

3. Observed (black) and predicted (colored) winds speeds for 15 July 2010–19 July 2010 at BSB. Top panels are WindNinja predictions. Bottom panels are NWP predictions…………………..62

4. Observed (black line) and predicted (colored lines) wind speeds for R2 located 5 km southwest of BSB on the Snake River Plain. Solid colored lines are NWP and dashed colored lines are WindNinja………………………………………………………………………………………..63
5. Observed (black) and predicted (colored) winds speeds for 18 July 2010 at BSB. Top panels are WindNinja predictions. Bottom panels are NWP predictions. .................................64

6. Root mean squared error in wind speed (left) and wind direction (right) at BSB for the entire five-day evaluation period \( N = 6360 \) and downslope \( N = 2650 \), upslope \( N = 1113 \), and synoptically-driven \( N = 1325 \) periods within the five-day period. Sample size, \( N = \) number of hours x number of sensor locations. ........................................................................67

7. Observed (black) and predicted (colored) winds speeds for 15 August 2011—19 August 2011 at SRC. Top panels are WindNinja predictions. Bottom panels are NWP predictions........69

8. Observed (black) and predicted (colored) winds speeds for 16 August 2011 at SRC. Top panels are WindNinja predictions. Bottom panels are NWP predictions.............70

9. Predicted wind fields from WRF-NARR (left) and WRF-UW (right) for 0600 August 16, 2011 at SRC during a surface pressure-driven easterly flow event. Shaded box indicates SRC study area. The black line indicates the general path of the Salmon River in this region...........72

10. Root mean squared error in wind speed (left) and wind direction (right) at SRC for the entire five-day evaluation period \( N = 3240 \) and downslope \( N = 1161 \), upslope \( N = 783 \), and synoptically-driven \( N = 405 \) periods within the five-day period. Sample size, \( N = \) number of hours x number of sensor locations. .........................................................75

Chapter 4

1. Location and extent of the area burned by the Jefferson Fire. Image courtesy of Google Earth.......................................................................................................................86

2. Instrumentation installed at the site .................................................................................................................................87

3. Pre-fire (left) and post-fire (right) vegetation at the study site .................................................................88

4. Time series photos of a single ground cover plot .........................................................................................91

5. Overview of post-fire meteorology and sediment transport from 10 August 2010 to 16 July 2011. \( \text{PM}_{10} \) concentrations are 5-min averages measured at 2 m above the soils surface. Horizontal sediment flux is the flux within a 2 m height above the soil surface; bars represent the total horizontal sediment flux for the sampling interval .........................................................96

6. Average and maximum \( \text{PM}_{10} \) vertical fluxes calculated from \( \text{PM}_{10} \) gradients above and below a height of 5 m. \( F_{v,2-5} \) is \( \text{PM}_{10} \) vertical flux calculated from gradient between 2 and 5 m. \( F_{v,5-10} \) is \( \text{PM}_{10} \) vertical flux calculated from gradient between 5 and 10 m ...........................................98

7. Observed wind speed, wind direction, friction velocity, and \( \text{PM}_{10} \) concentration for specific wind erosion events. \( \text{PM}_{10} \) concentrations were only measured at the 2-m height during the
September 2010 event. Vectors indicate wind direction (arrow pointing to the right indicates wind from the west) and speed (magnitude of the vector). Note changes in the scale of the y-axes.

8. MODIS satellite imagery showing the burn scar on 19 July 2010 (left) and a dust plume originating from the burned area on 5 September 2010 (right). Arrows indicate the ignition point of the fire.

9. Wind-blown sediment trapped behind straw bales protecting a county road downwind of the burned area in early April 2011, eight months after the fire.
ATTRIBUTION

This dissertation presents research related to two field studies and one modeling study: high resolution observations of the near-surface wind field on an isolated mountain and in a steep river canyon (Chapter 2); effect of model horizontal grid resolution on near-surface wind predictions in complex terrain (Chapter 3); and wind erosion from a sagebrush steppe burned by wildfire (Chapter 4). Natalie Wagenbrenner is the primary author for each of these manuscripts; however, the results presented in this dissertation represent efforts and contributions from many collaborators. Dr. Brian Lamb has contributed to all aspects of this work by providing guidance on scientific ideas and analysis methods, facilitating access to datasets used in the model evaluations work, and reviewing drafts of scientific manuscripts and presentations related to this work. Dr. Bret Butler, Jason Forthofer, and Kyle Shannon of the Missoula Fire Sciences Laboratory were instrumental in designing and coordinating the wind observation field campaigns and reviewing draft manuscripts related to this work (Chapter 2). Dr. Dennis Finn of the NOAA-FRD facilitated land access at the isolated mountain site and participated in the field campaign by contributing additional instrumentation to our observation network. Numerous people participated in the deployment and maintenance of the instrumentation at the two field sites, including Larry Bradshaw, Cyle Wold, Dan Jimenez, Mark Vosburgh, and Paul Sopko of the Missoula Fire Sciences Laboratory, Patrick O’Keefe, Kara Yedinak, and Gordon Dowler of Washington State University, and Ben Kopyscianski, Nicole Van Dyk, and Olga Martyusheva of the Rocky Mountain Research Station. Jason Forthofer and Kyle Shannon provided ideas, guidance, and programming and GIS assistance related to the model evaluations work (Chapter 3). Dr. Matthew Germino of the US Geological Survey and Dr. Pete Robichaud and Dr. Randy
Foltz of the Rocky Mountain Research Station contributed ideas, equipment, and assistance in maintaining instrumentation for the post-fire field campaign (Chapter 4).
CHAPTER ONE

INTRODUCTION

Wildfire is a natural phenomenon that plays an important role in many ecosystems. The landscapes and species that dominate the forests of the western US have evolved in the presence of wildfire and depend on it for continued existence. For example, there are tree species that require fire for seed regeneration, animals that depend on consumption of ground fuels for creating suitable habitats, and fish populations that rely on post-fire erosion effects to produce fresh gravels in stream channels for spawning. Wildfire is also the single largest disturbance in forested ecosystems and there is considerable debate as to whether current and future fire regimes will maintain the previous balance established between historical fire regimes and landscape processes.

Wildfires produce short-term negative impacts due to (1) direct effects of the fire on human health and safety, air quality degradation, and destruction of habitat, property, and resources and (2) indirect effects associated with post-fire land disturbance such as increased wind and water erosion, soil degradation, changes in preferential flow paths and stream networks, and changes in the surface energy budget. With wildfire activity projected to increase due to climate change (Flannigan et al., 2009) and accelerated development of the wildland urban interface (Theobald and Romme, 2007), it is becoming increasingly important to better understand and predict the role of fire and fire effects on the landscape. This need is also driven by fiscal motivations. The US Forest Service spends hundreds of millions of dollars each year on wildfire management activities. The majority of funds are used for fire suppression, including preventive operations like fuels thinning, and fire fighting activities during active fire incidents, but a significant amount is also used to support post-fire mitigation activities to protect “values at
risk” and to facilitate wildfire and post-wildfire research. Improved modeling tools for fire management could help to better understand and predict fire behavior as well as target resources more efficiently.

The application of modeling tools is one approach to improve our ability to understand and predict fire effects. Models are used for a variety of purposes, such as to isolate and investigate specific system variables or interactions, investigate responses to different types of forcing, better understand previous system behavior, or forecast future conditions. Wind is a major driving component in wildfire behavior and it also influences post-fire processes and can act as a key driver to re-shape landscapes after fire disturbance. Wind modeling is important for wildfire applications as it can help to answer critical questions regarding the rate and direction of fire spread, locating firefighter safety zones, fate and transport of wildfire ash, and smoke dispersion.

The goal of this work is to evaluate and improve a wind simulation tool to address these types of questions related to wildfire applications. This research improves the understanding of fire in complex terrain as well as associated post-fire effects in burned landscapes. Specific outcomes of this research include development of a comprehensive database of wind data with unprecedented spatial resolution, evaluation of a large suite of wind models in complex terrain, some of the first measurements of wind erosion from burned soils, and development of a PM$_{10}$ emissions algorithm for post-fire landscapes. Information and tools developed from this research will be directly useful for land managers and will help to guide partitioning of resources for wildfire applications.
The overall research goal is to improve the understanding and modeling of wind processes related to wildfire applications. This includes both active- and post-fire processes. This work contains three components:

(1) High resolution observations of the near-surface wind field on an isolated mountain and in a steep river canyon

(2) Effect of model horizontal grid resolution on near-surface wind predictions in complex terrain: evaluations with high resolution field observations from an isolated mountain and a steep river canyon

(3) Wind erosion from a sagebrush steppe burned by wildfire: measurements of PM$_{10}$ and total horizontal sediment flux; this work has been published in the journal Aeolian Research (Wagenbrenner et al., 2013)

These three components represent a substantial contribution to our understanding and ability to address the issues of fire in complex terrain and the associated potential for wind erosion from post-fire landscapes. In particular, this research produces a unique and substantial database of winds in complex terrain, which will be made available to the research community for analysis and model evaluation. This work also reports some of the first wind erosion measurements over a post-fire landscape. Further, the model development and evaluation based on each set of measurements will contribute to our ability to manage wildfires and the associated post-fire impacts.
References


CHAPTER TWO

HIGH RESOLUTION OBSERVATIONS OF THE NEAR-SURFACE WIND FIELD ON AN ISOLATED MOUNTAIN AND IN A STEEP RIVER CANYON

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1. Introduction

Predictions of terrain-driven winds are important in regions with complex topography for a number of issues, including wildland fire behavior and spread (Sharples et al., 2012; Simpson et al., 2013), transport and dispersion of pollutants (Jiménez et al., 2006; Grell, et al., 2000), simulation of convection-driven processes (Banta, 1984; Langhans et al., 2013), wind energy applications (Chrust et al., 2013; Palma et al., 2008), and climate change impacts (Daly et al., 2013). Numerous efforts have focused on improving boundary-layer flow predictions from numerical weather prediction (NWP) models by either reducing the horizontal grid size in order to resolve finer scale topographical features and their effects on atmospheric flow (Lundquist et al., 2010; Zhong and Fast, 2013) or adding new parameterizations to account for unresolved terrain features (Jiménez et al., 2012). Because NWP simulations are computationally demanding and suffer from inherent limitations of terrain-following coordinate systems in steep terrain (Lundquist et al., 2010), a number of high resolution diagnostic wind models have also been developed to downscale wind predictions from NWP models in order to meet the needs of the aforementioned applications (e.g., Beaucage et al., 2012). There are limited observational data available, however, to evaluate and improve such high resolution models. This paper describes a research program in which wind data were collected at very high spatial resolution under a range of meteorological conditions for two different types of complex terrain features. The datasets collected during this program enhance the archive of observational data for evaluating high resolution models. All of the data from the field program are available in a community web-based data portal.

Fine-scale changes in topography and vegetation substantially alter the flow field through mechanical effects, such as flow separation around obstacles, enhanced turbulence
from increased surface roughness, and speed-up over ridges, and through thermally-driven flows induced by local differential surface heating in steep terrain (Banta, 1984; Banta and Cotton, 1981; Chrust, et al., 2013). These local scale flow effects are critical for surface wind-sensitive processes, such as wildland fire behavior, where the near-surface wind is often the driving meteorological variable for fire rate of spread (Rothermel, 1972; Sharples et al., 2012). In order to capture these terrain-induced effects, wind modeling in complex terrain requires that surface characteristics, including terrain, vegetation, and their interactions with the atmosphere, be resolved at a high spatial resolution to provide accurate predictions of the near-surface flow field.

Although diagnostic wind models do not typically employ sophisticated boundary layer schemes in their flow solutions, they often incorporate parameterized algorithms for specific boundary layer effects, such as thermally-driven winds (e.g., diurnal slope flows) and non-neutral atmospheric stability (Forthofer et al., 2013; Scire et al., 2000). Evaluation of such schemes has been limited by the types of terrain features and range of meteorological conditions represented in available observational datasets. Two of the most widely used datasets for evaluation of high resolution wind predictions are from relatively simple geometry, low elevation hills investigated for wind energy applications (Berg et al., 2011; Taylor and Teunissen, 1987). Wind energy research has focused on relatively simple terrain because winds in complicated terrain are more difficult to reliably forecast and have higher turbulence that reduces the life of the turbines. These studies of idealized field sites have produced useful data for investigating the effects of simple terrain obstructions on average atmospheric flow and identifying specific deficiencies in numerical flow solutions; however, such sites represent relatively gentle terrain compared to the wide range of regions where
terrain-induced wind predictions are important. As a result, these data do not provide sufficient test data for evaluating spatial representation of modeled flows for commonly occurring types of terrain features, such as isolated terrain obstacles with complex geometries, dissected montane environments, and steep river canyons. Other types of observational studies, such as those designed to investigate boundary layer evolution or convection-driven processes, have focused on characterizing the vertical distribution of wind, temperature, and moisture, but do not typically characterize the spatial variability in the near-surface wind field. Examples of the types of flow phenomenon that are of interest for high resolution model evaluations include 1) local boundary 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 this paper, we describe a field campaign to collect high resolution wind data from two different types of terrain features, provide an overview of the data, with particular emphasis on the spatial characteristics of the surface wind measurements, and describe some unique flow features at each site. The specific objectives of this work were to: 1) collect detailed high resolution wind data over a range of meteorological conditions for two different types of complex terrain features; 2) provide an overview of the local meteorology and predominant flow field at each site; 3) detail specific flow features unique to each site; and 4) describe public access to these wind datasets. The data collected during this field campaign are used in a companion paper (Wagenbrenner et al., in Preparation) to evaluate several different NWP models and downscaling methods.

2. Instrumentation
Two field sites were each instrumented with a network of surface wind sensors deployed over a several month period and supplemented with short-term deployment of several 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) were used to measure 3.3-m wind speeds and directions 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 (Table 1; Fig. 1) 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 relative humidity, air temperature, wind speed and direction, solar radiation, and precipitation at two locations (Table 2; Fig 1).
Table 1. Sonic anemometer and vertical profiling sensor details.

<table>
<thead>
<tr>
<th>ID</th>
<th>Site</th>
<th>Sensor</th>
<th>Model</th>
<th>Time Period</th>
<th>Averaging Period</th>
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<td>BSB</td>
<td>Sodar</td>
<td>Scintech</td>
<td>14 Jul–15 Jul 2010</td>
<td>30-min</td>
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<tr>
<td></td>
<td></td>
<td>Sonic</td>
<td>ATI</td>
<td>14 Jul–18 Jul 2010</td>
<td>10 Hz</td>
</tr>
<tr>
<td>WSU2</td>
<td></td>
<td>Sodar</td>
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<td>15 Jul–19 Jul 2010</td>
<td>30-min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>31 Aug–1 Sep 2010</td>
<td>30-min</td>
</tr>
<tr>
<td>ST1</td>
<td>SRC</td>
<td>Weather station</td>
<td>Viasala, WXT CSAT3</td>
<td>16 Aug–12 Sep 2011</td>
<td>15-min</td>
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<tr>
<td></td>
<td></td>
<td>Sonic</td>
<td></td>
<td>18 Aug–19 Aug 2011</td>
<td>10 Hz</td>
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<tr>
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<td>Sodar</td>
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<td>29 Aug–31 Aug 2011</td>
<td>30-min</td>
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<td></td>
<td>Sonic</td>
<td>ATI</td>
<td>17 Aug–12 Sep 2011</td>
<td>15-min</td>
</tr>
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</table>

1BSB = Big Southern Butte; SRC = Salmon River Canyon.
Table 2. Radiosonde launches at BSB and SRC. Times are local time.

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>Time of launch</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSB</td>
<td>August 31 2010</td>
<td>16:57</td>
</tr>
<tr>
<td></td>
<td>September 1 2010</td>
<td>16:59</td>
</tr>
<tr>
<td></td>
<td>September 2 2010</td>
<td>10:35</td>
</tr>
<tr>
<td>SRC</td>
<td>July 18 2011</td>
<td>11:28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13:56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15:50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18:14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20:00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>21:32</td>
</tr>
</tbody>
</table>

¹BSB = Big Southern Butte; SRC = Salmon River Canyon.

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 (Fig. 1). Two field sites were selected to represent an isolated terrain obstacle and a steep, non-forested river canyon. The first field campaign occurred during June–September 2010 at Big Southern Butte (BSB) in southeastern Idaho. The second campaign occurred during July–September 2011 in the Salmon River Canyon (SRC) in north central ID. These sites provided a range of wind conditions representative of generally dry, inland, sunny summertime periods.
Fig. 1. Sensor layouts at the Salmon River Canyon (a) and Big Southern Butte (b, c). Black circles indicate surface sensors. Red diamonds indicate sonic anemometers and vertical profiling sensors.

An array of 53 surface sensors was deployed on BSB during 15 Jun 2010–9 Sep 2010 (Fig. 1). 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 during 15 Jul–18 Jul 2010 and immediately northeast of the butte during 31 Aug–1 Sep
2010 (Fig. 1; Table 1). A tower of sonic anemometers was deployed 2 km southwest of the butte during 14 Jul–18 Jul 2010 (Fig. 1; Table 1). Three RadioSonde launches were conducted at BSB during 31 Aug–2 Sep 2010 (Table 2).

An array of 27 surface sensors was deployed in three cross-river transects at SRC during 14 Jul–13 Sep, 2011 (Fig 1). Sodars and sonic anemometers were operated during 16–18 Jul and 29–31 Aug 2011 (Table 1). 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 (Fig. 1). 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 (Fig. 1). Two weather stations monitored air temperature, relative humidity, precipitation, solar radiation, wind speed, and wind direction during the monitoring period; 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 (Fig. 1). Six RadioSonde launches were conducted on 18 Aug 2011 (Table 2).

3. Site Descriptions

3.1. Big Southern Butte (BSB)

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, 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 (Fig. 2). 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 (Fig. 2). 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.

Fig. 2. Snake River Plain and prominent drainages surrounding the BSB study site.

Summertime mesoscale meteorology in this region is characterized by the frequent passage of frontal systems, which bring westerly winds that become channeled into southwesterly flow up the Lower Snake River Plain (LSRP) toward BSB (e.g., Andretta, 2002). This same westerly synoptic flow passes over the central mountains to the north of BSB and surface winds become channeled into northerly flow down the Big Lost, Little Lost, and Birch
Creek drainages and onto the USRP. This northerly flow approaches BSB from the USRP, eventually converging with the southwesterly flow somewhere in the vicinity of BSB in the Snake River Plain Convergent Zone (SPCZ) (Andretta, 2002; Andretta and Hazen, 1998). The location of the SPCZ shifts up or down the SRP depending on the strength of the low-level winds over the USRP versus the LSRP (Andretta, 2002).

3.2. Salmon River Canyon (SRC)

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, with some timber in the higher elevations on the north aspects. There were prominent side drainages entering SRC on the east and west end of our study area (Fig. 1). Our instrumentation was deployed away from forested areas, so as to avoid effects of the forest canopy on the wind flow.

4. Analysis Methods and Terminology

The data analyses in this paper focus on the surface wind measurements and terrain influences on the surface flow characteristics determined from these measurements. Data from additional instruments, such as vertical profilers, are presented when appropriate to facilitate discussion of the surface flow results. All data are available in public archives as described in section 6.
4.1. Partitioning surface data into flow regimes

The surface wind data were partitioned into four distinct wind regimes in order to facilitate the analysis of typical diurnal flows in the absence of strong synoptic forcing and high wind events during periods of strong synoptic forcing. The four wind regimes are:

(1) a downslope regime, which included downslope and down-valley flows, forced by nighttime surface cooling

(2) an upslope regime, which included upslope and upvalley flows, forced by daytime surface heating

(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).

(4) a synoptically forced regime, during which the normal diurnal cycle was disrupted by larger-scale flows and local flows typically correlated with gradient level winds due to mechanically-induced turbulent mixing in the boundary layer.

The first three are analogous to the wind regimes described in Banta and Cotton (1982) and are referred to collectively in this paper as the diurnal wind regime. The fourth regime was included here as the field sites investigated in this study frequently experienced periods of intense large-scale synoptic forcing, which generated high surface wind speeds and sufficient mechanical mixing to overcome the diurnal flow regime.

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. Sensors R2 and NM1 were chosen to be the representative sensors at BSB and SRC, respectively. R2 was located on the USRP approximately 5 km southwest of the butte. NM1 was located on the north side of the SRC at 1530 m ASL, roughly three-quarters of the distance from the canyon bottom to the ridgetop. These sensors were chosen because they appeared to be the least influenced by the terrain and most representative of the gradient winds. Threshold velocities of 6 and 5 m s\(^{-1}\) were chosen for BSB and SRC, respectively (Fig 3). Speeds below these thresholds fall within the range of diurnal wind flows reported in the literature (Horst and Doran, 1986) and visual inspection of the vector maps further confirmed this choice of threshold wind speeds, as all four regimes were clearly identified by the surface flow patterns at each site.
After filtering out the synoptically driven periods, the remaining data were then partitioned into regimes (1)–(3) based on visual inspection of the hourly vector maps. Periods that exhibited clearly defined downslope flow were partitioned into (1). Periods that exhibited clearly defined upslope flow were partitioned into (2). And afternoon periods during which the upslope regime was disturbed were partitioned into (3). Transition periods from one regime to another were also identified based on visual inspection of the hourly vector maps.

4.2. Data averaging

Surface wind observations were averaged over a 10-min period at the top of each hour to represent an average speed valid at the top of each hour. This averaging scheme was chosen to be representative of wind speeds from NWP forecasts. Although NWP output is valid at a particular instant in time, there is some inherent averaging in these ‘instantaneous’ predictions. The averaging associated with a given prediction depends on the time-step used in the NWP
model, but is typically on the order of minutes. The 10-min averages are referred to in the text as hourly wind speeds and directions.

Hourly vector maps were used to visualize the spatial patterns of the wind fields for classifying flow regimes. The vector maps were produced by averaging the hourly flow data for each sensor during a given hour for all the data that fell into one of the following categories: (1) strong synoptic forcing or (2) weak synoptic forcing (i.e., diurnal winds dominate). 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. Partitioning of data into weak vs. strong synoptic forcing is described in Section 4.1.

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) and diurnal wind contour plots were produced using the metvurst library (Salabim, 2013).

5. Results and Discussion

Results for BSB are presented in section 5.1. Results for SRC are presented in section 5.2. Average flows for the diurnal wind regimes are presented for each site and then the disturbance to the diurnal wind regime by synoptic-scale forcing is described. Transitions within the diurnal wind regime (e.g., upslope to afternoon regime) occurred at roughly the same time of day throughout the monitoring periods, with no discernible differences between average hourly vector maps for the first and second half of the monitoring period. Thus, results for diurnal winds are reported as averages for the entire monitoring period. This is reasonable since monitoring periods were during summertime at both sites. All times are reported as local time.
5.1. BSB

5.1.1. Diurnal winds: upslope, afternoon, and downslope regimes

Sunrise ranged from 0600 to 0700 during the monitoring period. Upslope winds formed between 0800 and 0900 and the upslope regime was fully established by 1000 and persisted until around 1200. Upslope winds peaked around 1100. This regime was characterized by thermally-driven upslope winds on all sides of the butte flowing up from the surrounding SRP (Fig 4). The timing of onset and occurrence of peak winds in the upslope regime was consistent with Banta and Cotton (1982) and Geerts et al. (2008), who reported peaks in upslope flow before local solar noon (LSN) for relatively small mountains. Others have reported peaks in upslope flow after LSN for larger mountain ranges (McNider and Pielke, 1981; Reiter and Tang, 1984). Geerts et al. (2008) discussed this discrepancy in the reported timing of upslope flows for different mountain ranges and described the development of upslope winds as scaling with the size of the mountain. BSB is a relatively small isolated mountain (horizontal scale of ~5 km and vertical scale of ~800 m above the surrounding SRP) and so establishment of the upslope regime prior to LSN fits with this scaling theory. Upslope flows persisted about two hours longer than those at the South Park site in Colorado reported by Banta and Cotton (1982). This difference could be attributed to the upwind terrain, as westerly flows from the Rocky Mountains were likely more turbulent than the southwesterly flows approaching BSB from the SRP, and perhaps were able to more quickly entrain the developing convective boundary layer (CBL) at South Park.
Wind speeds in the upslope regime ranged from 1.8 to 7.3 m s\(^{-1}\), with an average of 3.1 m s\(^{-1}\) (Table 3). There were a few ridgetop sensors that appeared to be decoupled from the diurnal flow regime on the butte (discussed in detail at the end of this section); if these sensors are removed, the wind speeds ranged from 1.8 to 4.5 m s\(^{-1}\), with an average of 3.0 m s\(^{-1}\). These are higher speeds than those reported by Geerts et al. (2008), but similar to the range reported by Banta and Cotton (1982). Differences in the reported range of speeds between this study and Geerts et al. (2008) could be attributed to differences in the actual quantities reported. Geerts et al. (2008) used an averaging scheme to calculate a mean anabatic wind that is a function of the circumference of the polygon obtained by connecting the midpoints between observation stations.
around the mountain. Also, their wind measurements were made at 10 m AGL, while ours were at 3 m AGL. Upslope wind speeds were typically higher further up the slopes than lower on the butte (Fig. 5a), although the highest average speed was recorded at R15 (elevation 1970 m, roughly half the height of BSB). Sensor R15 was located on a ridgetop exposed to the prevailing southwesterly winds and we believe this sensor may have been decoupled from the diurnal flow regime on the butte and more correlated with the large-scale flows; this is also confirmed by contour plots of wind direction over time (Fig. 6) and is discussed in further detail at the end of this section.

Table 3. Measured wind speeds (m s\(^{-1}\)) during upslope, downslope, and convective mixing regimes at Big Southern Butte (BSB) and Salmon River Canyon (SRC). Decoupled ridgetop locations (sensors R26, R35, TSW7, and R15) were omitted from BSB averaged; speeds in parentheses include ridgetop sensors.

<table>
<thead>
<tr>
<th>Site(^{1})</th>
<th>Wind Speed</th>
<th>Upslope (1100 LT)</th>
<th>Convective Mixing (1600 LT)</th>
<th>Downslope (0000 LT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSB</td>
<td>Min (m s(^{-1}))</td>
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<td>2.3</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Max (m s(^{-1}))</td>
<td>4.5 (7.3)</td>
<td>8.1</td>
<td>7.5 (12.0)</td>
</tr>
<tr>
<td></td>
<td>Mean (m s(^{-1}))</td>
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<td>4.1</td>
<td>3.4 (3.7)</td>
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<tr>
<td>SRC</td>
<td>Min (m s(^{-1}))</td>
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<td>0.92</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Max (m s(^{-1}))</td>
<td>4.0</td>
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<td>4.1</td>
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<td></td>
<td>Mean (m s(^{-1}))</td>
<td>2.4</td>
<td>2.5</td>
<td>1.2</td>
</tr>
</tbody>
</table>

\(^{1}\)BSB = Big Southern Butte; SRC = Salmon River Canyon.
Fig. 5. Average wind speeds for sensors at three slope locations (low, mid, and high) along three transects during the (a) upslope (1100 LT) and (b) downslope (0000 LT) flow regimes at BSB.
Fig. 6. Contour plots of hourly wind frequencies and corresponding wind speeds for a transect on the southwest slope of Big Southern Butte (left panels) and a transect on the northeast slope of Big Southern Butte (right panels). Panels are ordered from higher-elevation sensors (top panels) to lower elevation sensors (bottom panels). Periods of synoptic forcing were removed from this data.

Upslope winds transitioned to the afternoon regime between 1200 and 1300. This transition is most notable by an increase in wind speeds on the southwest side of the butte and a shift in the wind directions on the northeast side of the butte (Fig. 4). This regime included local flows that generally correlated with the gradient level winds above the ridgetops due to convective mixing in the deep afternoon boundary layer. Convective mixing was fully established by 1400 and persisted until around 2000. Wind speeds peaked around 1500 and were fairly consistent through 1900. The onset of the afternoon regime was slightly later in the day than that reported by Banta and Cotton (1982) and could be due to less turbulent approach flow
at BSB as discussed above. During the afternoon regime, the prevailing southwesterly flow was routed around the northwest and southeast sides of the butte (e.g., sensors R9 and R13). Wind speeds were highest on the ridgetops and southwest slopes and lowest on the northeast slopes (Fig. 4). There was some apparent recirculation on the northeast side of the butte as well as in some of the side drainages (Fig. 4). Wind speeds in the afternoon regime ranged from 2.3 m s\(^{-1}\) to 8.1 m s\(^{-1}\) with an average of 4.1 m s\(^{-1}\).

Sunset ranged from 2030 to 2130 during the monitoring period. The afternoon regime began to decay and transition into downslope winds between 2100 and 2200. The downslope regime was fully established by 2300 and persisted until around 0800. Peak downslope winds occurred around 0000. The timing of onset and occurrence of peak winds in the downslope regime agreed with observations reported in Banta and Cotton (1982). Downslope flows are clearly shown in the hourly vector plots, with flows going from the top of the butte down all side drainages around the butte and flowing out onto the SRP (Fig. 4). Wind speeds in the downslope regime ranged from 1.3 to 12.0 m s\(^{-1}\), with an average of 3.7 m s\(^{-1}\). If the decoupled ridgetop sensors are removed, the range was 1.3 to 7.5 m s\(^{-1}\), with an average of 3.4 m s\(^{-1}\) (Table 3). This range is similar to that reported in Banta and Cotton (1982) and slightly larger than that reported in Horst and Doran (1986). Others have proposed an acceleration of flow with downslope distance due to a thickening of the katabatic layer with downslope distance (Horst and Doran, 1986); however, we did not observed a consistent trend in wind speed with location on the slope (low vs. high) during the downslope regime (Fig. 5b).

Diurnal winds dominated the local flows on and around the butte under periods of weak synoptic forcing. During these periods, flow on and around BSB was decoupled from the large-scale atmospheric flows, except for high-elevation ridgetop sensors (R26, R35, TSW7) and one
exposed mid-elevation ridge sensor (R15). This decoupling is evident from the vector maps (Fig. 4) and is also confirmed by the contour plots which show that these ridgetop locations do not experience the strong diurnal shifts in wind direction that other locations on and around the butte experience (Fig. 6, 7). This ridgetop decoupling likely occurred because these locations were high enough in the atmosphere to protrude out of the nocturnal boundary layer (NBL) and the morning-time developing shallow CBL. Thus, the ridgetop winds were coupled with the large-scale flows during all periods of the day. During nighttime hours the ridgetop locations would experience residual layer winds and would only be coupled with the rest of the flow on and around the butte once the residual layer was entrained by the growing shallow CBL and the convective mixing regime was fully established. This proposed structure is confirmed by the vector plots, which show that ridgetop winds did not change much from one regime to the next and only correlated with winds at other nearby locations on the butte during the convective mixing regime (Fig. 4).
Fig. 7. Contour plots of hourly wind frequencies and corresponding wind speeds for four ridgetop locations at Big Southern Butte. Periods of strong synoptic forcing were removed from this data.

5.1.2. Synoptic disturbance of diurnal winds
Under periods of strong synoptic forcing, such as the passage of a cold front, the diurnal wind regime was disrupted and a synoptically-forced regime persisted. Two types of flow events occurred within the synoptically-forced regime, one during daytime hours and one during nighttime/early morning hours (Fig. 8).
Fig. 8. Characteristic synoptically-driven regime events during the passage of a frontal system (1800 LT) and during synoptically-enhanced downvalley flow on the Snake River Plain (2300 LT) at BSB during June-September 2010. Vectors represent the average hourly flow at a given sensor. Periods of weak synoptic forcing were removed prior to averaging. Lower strip is zoomed out to show entire study area.

Synoptically-driven events are subject to the flow mechanisms related to formation of the SPCZ described in section 2.2.1. We observed that during daytime hours, flows were consistently from the southwest, but that during nighttime and early morning hours, flows were generally from the northeast (Fig. 8). This suggests that the SPCZ tended to be northeast of BSB
during daytime hours, but southwest of BSB during nighttime and early morning hours. The southwest flows are referred to as ‘synoptically-driven upvalley’ flows and the northeasterly flows are referred to as ‘synoptically-driven downvalley’ flows. It is interesting that wind speeds were generally higher on the ridgtops and southwest (leeward) side of BSB than on the northeast (windward) side during periods of synoptically-driven downvalley flows. Perhaps this is because the maximum in the low-level winds in the northeasterly flow occurred at some higher elevation in the atmosphere and was not well-mixed with near-surface winds due to nighttime temperature stratification in the NBL. Perhaps the northeasterly flow passing over the ridgtops also enhanced the downslope flow on the southwest side of BSB, thus producing stronger winds on this side as compared to the northeast (windward side).

Wind speeds during the synoptically-driven upvalley and downvalley flows ranged from 2.9 to 20.3 m s⁻¹, with an average of 7.1 m s⁻¹, and 0.1 to 24.4 m s⁻¹, with an average of 6.0 m s⁻¹, respectively. The diurnal slope flows on BSB were completely overtaken by the larger-scale flows in this regime (Fig 8 vs. Fig. 4). Mechanical channeling of the gradient level winds by the surrounding terrain coupled with the movement of the SPCZ relative to BSB resulted in upvalley and downvalley winds on the SRP that coincided with the typical diurnal cycle.

5.2. SRC

5.2.1. Diurnal winds: upslope, afternoon, and downslope regimes

Sunrise ranged from 0500 to 0630 during the monitoring period. Upslope winds formed around 0900 and the upslope regime was fully established by 1000 and persisted until around 1500. Upslope winds peaked around 1200 and were fairly consistent through 1400. The upslope regime was characterized by thermally-driven upslope winds on both sides of the canyon as well
as up smaller side drainage slopes (Fig. 9). The one notable exception was sensor NM2, which experienced easterly or southeasterly flow during most periods of the day (Fig. 9). We believe this sensor was perhaps in a local recirculation zone formed in the small side drainage where this sensor was located; this is discussed at the end of this section. Wind speeds in the upslope regime ranged from 0.75 to 4.0 m s\(^{-1}\), with an average of 2.4 m s\(^{-1}\) (Table 3).

Fig. 9. Upslope (1100 LT), afternoon (1600 LT), and downslope (0000 LT) regimes at SRC during periods of weak synoptic flow during July–September 2011. Vectors represent the average hourly flow at a given sensor. Periods of strong synoptic forcing were removed prior to averaging.

Wind speeds tended to be highest at the upper elevation sensors around the onset of the upslope regime at 0900 (Fig. 10). As the upslope regime developed, wind speeds peaked around 1100 and were highest at the mid-elevation sensors (Fig. 10) and this trend continued through 1300. The NW and SE transects do not follow these trends. The NW transect had consistently lower speeds at the mid-elevation sensor during all periods of the upslope regime. This could be because NW3 was located slightly off of the ridge on a northwest aspect and perhaps decoupled from the flow along the rest of the NW transect. The SE transect had consistently higher speeds at the mid-elevation sensor (SE4). The higher speeds at SE4 could be because this sensor was located on a ridge exposed to a prominent side drainage (Lake Creek) just to the east of our study.
area (Fig. 1). Flows out of this Lake Creek drainage could have influenced this sensor more than others along the SE transect due to its location on the ridge and steep terrain to the southeast (Fig. 1).

![Average wind speeds for sensors at three slope locations (low, mid, and high) along five transects during three hours of the upslope (top panels) and downslope (bottom panels) flow regimes at SRC. Blue and red lines are transects on the south and north side of the river, respectively.](image)

Fig. 10. Average wind speeds for sensors at three slope locations (low, mid, and high) along five transects during three hours of the upslope (top panels) and downslope (bottom panels) flow regimes at SRC. Blue and red lines are transects on the south and north side of the river, respectively.

We did not observe an afternoon convective mixing at SRC as we did at BSB. This is consistent with Banta and Cotton (1982) who noted that a true convective mixing regime is not well documented in narrow mountain canyons, likely due to the strong channeling effect exerted by the canyon on the flow. The afternoon regime at SRC was characterized by a change from upslope to upvalley winds around 1500. This afternoon upvalley regime was fully established by
1600 and persisted through 1900. The most notable change between the upslope regime and the afternoon regime was the shift in wind direction from up the canyon walls (northerly or southerly flow) to upriver (westerly flow), especially for the lower-elevation sensors. Daytime gradient level winds were typically from the west (downriver), so it could be difficult to determine if this afternoon shift in wind direction was driven by convective mixing of gradient level winds down into the canyon or the formation of thermally-driven upvalley flow within the canyon. The fact that this change in wind direction was most notable in the lower elevation sensors (Fig. 9) points to a thermally-driven mechanism. Wind speeds were fairly consistent throughout this time period and ranged from 0.92 to 4.2 m s⁻¹, with an average of 2.5 m s⁻¹ (Table 3). Wind speeds were the lowest near the canyon bottom except for the SE and NW transects, which had the lowest speeds at high- and mid-elevation sensors (SE3 and NW3). Both of these sensors were located slightly off the main ridge. It is interesting that the lowest sensors responded most noticeably to the shift from upslope to upvalley flow with a change in wind direction, but that the highest speeds were still observed at the upper elevation sensors.

Sunset ranged from 1900 to 2030 during the monitoring period. Upvalley flow began to weaken and transition to downslope flow between 2000 and 2100. The downslope regime was fully established by 2200 and persisted until around 0700. Peak wind speeds in the downslope regime occurred around 2200. Wind speeds in the downslope flow regime ranged from 0.33 to 4.1 m s⁻¹, with an average of 1.2 m s⁻¹ (Table 3). Wind speeds tended to increase with upslope distance (Fig. 11), with the exception of the SE transect, likely due to the location of SE3 and SE4 as discussed above. This trend was consistent throughout the duration of the downslope regime.
Fig. 11. Average wind speeds for sensors at three slope locations (low, mid, and high) along five transects during the afternoon flow regime (1700) at SRC. Blue and red lines are transects on the south and north side of the river, respectively.

Diurnal trends were further inspected for the NM transect. We chose this transect for further investigation as this transect was not located near any prominent side drainages and likely exhibited the simplest flow characteristics. Contour plots showed a strong diurnal signal for all sensors in this transect (Fig. 12), indicating that diurnal flows are a major flow feature in the SRC. Winds were from the east or southeast in the early morning and from the west/northwest in the afternoon and the highest speeds occurred at the upper elevation sensors during early morning hours. One exception was the NM2 sensor, which rarely experienced winds from the west/northwest and did not experience a morning time peak in wind speed. This sensor was located slightly off a mid-slope ridge on a slope with a northwest aspect. We suspect that this location was possibly a zone of recirculation. The lowest sensor, NM4, also did not experience a morning peak in wind speed and rarely experienced winds from the northeast. The highest
speeds occurred during periods of synoptic disturbance, which we believe had more of an effect at upper elevations in the SRC than lower ones near the river bottom. This is discussed further in the next section.
Fig. 12. Contour plots of hourly wind frequencies and corresponding wind speeds for the NM transect at SRC. NM1 is near the ridgetop. NM4 is near the canyon bottom. All data were used.

5.2.2. Synoptic disturbance of diurnal winds
We observed two types of synoptic disturbances to the diurnal wind regime in the SRC (Fig. 13). One is associated with the passage of frontal systems from the west, which brings strong westerly gradient winds. The other appears to be associated with the presence of an east-west pressure gradient that generates strong morning-time easterly flow.

Fig. 13. Characteristic synoptically driven upvalley flow (1500 LT) and downvalley flow (1100 LT) at SRC during July–September 2011. Vectors represent the average hourly flow at a given sensor. Periods of weak synoptic forcing were removed prior to averaging.

During the passage of frontal systems, westerly winds are channeled up the river canyon and most sensors in SRC (with the exception of those located in side drainages) experienced westerly flow. These events tended to occur in during mid-afternoon hours. Wind speeds during this type of synoptic disturbance ranged from 2.1 to 5.7 m s⁻¹, with an average of 3.8 m s⁻¹.

The highest observed wind speeds in the SRC were from the east during morning hours (Fig. 12, 13). Wind speeds during these pressure-driven downvalley events ranged from 0.84 to 9.1 m s⁻¹, with an average of 3.1 m s⁻¹. These events occurred roughly every few days and appeared to be induced by a surface pressure gradient formed when a thermal trough existed on the Columbia
Plateau and high pressure existed to the east of SRC (Fig. 14). An east-west pressure gradient existed both at the surface level and 500 mb height on days when enhanced downvalley flow was observed. On days when the downvalley flow feature was not observed, there was no east-west pressure gradient at either the surface or 500 mb heights. The highest winds speeds during this type of flow event were observed at the upper elevations of the SRC (Fig. 15).
Fig. 14. Synoptic-scale pressure conditions conducive to enhanced easterly flow (left) and typical diurnal flow scenarios (right) at SRC. Top panel isobars are surface level pressures. Bottom panel isobars are 500 mb height pressures. (National Center for Environmental Prediction).
Fig. 15. Average wind speeds for sensors at three slope locations (low, mid, and high) along five transects during the synoptically driven upvalley (left) and synoptically driven downvalley (right) flow regimes at SRC. Blue and red lines are transects on the south and north side of the river, respectively.

6. Archived Data

All data are archived as downloadable SQLite databases. These databases along with tools to query, process, and visualize, the data are available at http://www.firemodels.org/index.php/windninja-introduction/windninja-publications. Additionally, the National Oceanic and Atmospheric Administration Field and Research Division (NOAA-FRD) operates a permanent mesonet system that consists of 35 15-m towers spread across the USRP and encompassing the BSB study area. The mesonet towers measure wind speed, wind direction, air temperature, relative humidity, and solar radiation. NOAA-FRD also operates a permanent wind profiling system and a radio acoustic sounding system (RASS) at a location approximately 10 km northwest of BSB. Mesonet data is described in Andretta (2002).

7. Conclusions
We have presented an analysis of two high-resolution surface wind datasets collected from a tall isolated mountain and a steep river canyon. The wind data was analyzed and presented in terms of four flow regimes: upslope, afternoon, downslope, and a synoptically-driven regime. These datasets constitute a unique inventory of surface wind measurements at very high spatial resolution under dry summertime conditions. Public access to the archived datasets and has been described.

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 strong synoptic forcing that enhanced either upriver or 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 under periods of weak synoptic forcing, only a transition from upslope to thermally-driven upriver flow.

The highest speeds measured at BSB occurred during the passage of frontal systems from the northeast during early morning hours and from the southwest during afternoon hours. 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. The fact that surface winds at both sites tended to be decoupled from large-scale flows under periods of weak synoptic forcing means that traditional operational weather model winds (i.e., with numerical grid resolutions of around 4 km or larger) are not likely to be good predictors of local winds in sub-grid scale complex terrain. 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 mean wind for a 4 km grid cell encompassing these terrain features would not be representative of actual surface winds at most locations on or within the terrain feature. 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.

8. Acknowledgements

The Department of Interior Bureau of Land Management Idaho Falls, ID field office facilitated the field campaign and Barry Sorenson provided critical advice on local conditions, access roads, and weather as well as permission to store equipment onsite during the deployment at Big Southern Butte. Thanks to Nicole Van Dyk, Olga Martyusheva, Jack Kautz, Peter Robichaud, and Ben Kopyscianski of the Rocky Mountain Research Station for help with the field installation and maintenance at the Salmon River site. Funding was provided by the Joint
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References


CHAPTER THREE

EFFECT OF MODEL HORIZONTAL GRID RESOLUTION ON NEAR-SURFACE WIND PREDICTIONS IN COMPLEX TERRAIN: EVALUATIONS WITH HIGH RESOLUTION FIELD OBSERVATIONS FROM AN ISOLATED MOUNTAIN AND A STEEP RIVER CANYON

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1. Introduction

A number of applications depend on wind predictions in complex terrain. Simulations of wildfire behavior, land surface-atmosphere fluxes, transport and dispersion of scalars, and wind energy forecasting all require predictions of wind flows in regions where rugged terrain 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, and enhanced surface roughness alter the flow field over spatial scales finer than those typically used by mesoscale numerical weather prediction (NWP) models.

NWP models compute gridded predictions of $u$, $v$, $w$, pressure, moisture, and heat on a 3-D computational domain. The computational domain is a 3-D volume comprised of multiple layers of horizontal grids. Each layer (grid) in the 3-D domain can be described in terms of an extent and resolution. The extent defines the bounds of the grid in the $x$-$y$ plane and the horizontal resolution defines the cell size (in the $x$-$y$ plane) of the grid. Typically the same resolution is used in the $x$ and $y$ dimensions (i.e., $dy = dx$) for all layers (grids) in the domain and thus, the horizontal resolution can be described by a single value. The vertical resolution between grids typically increases with height about the ground.

Mesoscale NWP models used for routine forecasting typically employ grids with horizontal resolutions of 4 km or larger and are generally restricted to resolutions of greater than 1 km, at which point sigma-based terrain-following coordinate systems begin to break down due to skewness in near-surface cells over rugged terrain (Lundquist et al. 2010; Mahrer 1984). This is a significant limitation of NWP models, since even a 1-km spatial resolution is coarse compared to the scales over which spatially varying terrain can impart effects on the local wind flow. For many applications, a 1-km horizontal resolution may not be sufficient to resolve
important features in the flow. Options exist for improving horizontal resolution in NWP models, but these options have their own limitations, which make them impractical for many applications. For example, a modified coordinate system, such as the immersed boundary method can be used (Lundquist et al. 2010) or models can be operated in large eddy simulation (LES) mode on finer-grid resolutions; however, these methods are not employed by operational NWP models running routine forecasts, and thus, not available to general users of these forecast products. In many cases, users wanting to obtain wind information for input into other predictive models do not have either the desire, computing resources, or expertise to run a NWP model, but simply want to extract this information from existing forecast products.

Dynamic downscaling is one option for improving coarse-scale winds from routine NWP model forecasts. NWP forecasts linked with higher-resolution wind simulation tools can produce more accurate wind predictions (Beaucage et al. 2012), as synoptic-scale forces and planetary boundary layer processes are resolved by the NWP model to generate an initial wind field that is then downscaled by the higher-resolution wind model to enforce conservation of mass and, in some cases momentum and energy, on the flow field on a higher-resolution grid that better resolves individual terrain features.

There are two types of steady-state models commonly used for downscaling NWP winds to higher resolution flow fields: 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 production and dissipation of turbulent kinetic energy (TKE) in the flow field. The least computationally intensive CFD approaches employ a Reynolds Averaging of the Navier-Stokes equations (RANS) model for TKE. 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 (e.g., to properly set up boundary conditions or to select a turbulence model), which many users do not have. These limitations have rendered CFD modeling impractical for many real-world operational applications, especially time-critical ones, such as modeling winds for operational fire weather forecasts, for example.

Mass-conserving models solve the conservation of mass equation, but do not consider TKE in the flow solution, 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 negligence of TKE in the flow solution, particularly in areas of enhanced production of turbulence, such as on the lee side of terrain features; however, mean flow solutions generated by mass-conserving models can yield accurate predictions in other regions, where TKE is less important to the flow, such as on the windward side of terrain features, where speed-up occurs. Additionally, parameterizations for certain flow effects, such as non-neutral atmospheric stability and diurnal slope flows, can be included within the mass-conserving equations to improve accuracy. Ultimately, the significant reduction of computational resources and time make mass-conserving models a reasonable alternative for many applications. In this work, we investigate the ability of a mass-conserving wind model, WindNinja (Forthofer et al. In Review; Forthofer 2007), for dynamically downscaling NWP model winds.

The goals of this work are to (1) investigate the effect of NWP model horizontal spatial resolution on the accuracy of near-surface wind predictions in complex terrain on spatial scales relevant for processes driven by local surface wind flows, such as wildland fire behavior (2) assess the ability of a mass-consistent wind model to improve these predictions through dynamic
downscaling. Wind predictions are investigated from three mesoscale NWP models operated on different horizontal grid resolutions: (1) Weather Research and Forecasting (WRF) at 4-km and 1.33-km resolutions; (2) North American Mesoscale Model (NAM) at 12-km resolution; and (3) High Resolution Rapid Refresh (HRRR) at 3-km resolution. Mesoscale model wind predictions are then compared to mesoscale winds dynamically downscaled with a mass-consistent high-resolution wind model, WindNinja (Forthofer et al. In Review; Forthofer 2007). Predictions are evaluated with surface wind data collected at high spatial resolution from an isolated butte and a steep river canyon (Wagenbrenner et al. In preparation).

2. Model descriptions and configurations

a. Weather Research and Forecasting (WRF)

WRF is a finite-difference NWP model that solves the non-hydrostatic, fully compressible Navier-Stokes equations (Skamarock et al. 2007). All of the NWP models investigated in this work use either the Advanced Research WRF (ARW) or the non-hydrostatic multi-scale model (NMM) core of the WRF model (Table 1). Routine WRF-ARW (hereafter, just WRF) forecasts with 4-km horizontal resolution were acquired from the University of Washington Atmospheric Sciences forecast system (www.atmos.washington.edu/mm5rt/info.html). These forecasts are referred to as WRF-UW. The outer 36-km domain of the WRF-UW simulations covers most of the western US and northeastern Pacific Ocean. This outer domain is initialized with NCEP Global Forecast System (GFS) 1-degree runs. The 36-km domain is nested down to 12 km, 4 km, and, more recently, an experimental 1.33-km grid. The 4-km domain investigated in this study covers the Pacific Northwest, including Washington, Oregon, Idaho, and portions of California, Nevada, Utah,
Wyoming, and Montana. Physical parameterizations employed by WRF-UW include the Noah Land Surface Model (Chen et al. 1996), Thompson microphysics (Thompson et al. 2004), Kain and Fritsch (1990) for convection, Rapid Radiative Transfer Model (RRTM) for longwave radiation (Mlawer et al. 1997), Duhdia (1989) for shortwave radiation, Yonsei University (YSU) boundary layer scheme (Hong et al. 2006). WRF-UW is run at 00z and 12z and generates hourly forecasts out to 84 hours.

Table 1. Model specifications. When values differ between field sites, the values for Salmon River Canyon are in parentheses.

<table>
<thead>
<tr>
<th>Model</th>
<th>Horizontal grid resolution</th>
<th>Number vertical layers</th>
<th>First layer height&lt;sup&gt;a&lt;/sup&gt; (m AGL)</th>
<th>Top height&lt;sup&gt;a&lt;/sup&gt; (m AGL)</th>
<th>Numerical core</th>
<th>Run frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAM</td>
<td>12 km</td>
<td></td>
<td></td>
<td></td>
<td>NMM</td>
<td>00z, 06z, 12z, 18z</td>
</tr>
<tr>
<td>WRF-UW</td>
<td>4 km</td>
<td>38</td>
<td>40</td>
<td></td>
<td>ARW</td>
<td>00z, 12z</td>
</tr>
<tr>
<td>HRRR</td>
<td>3 km</td>
<td>38</td>
<td>40</td>
<td></td>
<td>ARW</td>
<td>hourly</td>
</tr>
<tr>
<td>WRF-NARR</td>
<td>1.33 km</td>
<td>38</td>
<td>40</td>
<td></td>
<td>ARW</td>
<td>NA</td>
</tr>
<tr>
<td>WindNinja&lt;sup&gt;b&lt;/sup&gt;</td>
<td>138 (54) m</td>
<td>20</td>
<td>1.92 (1.76)</td>
<td>931 (851)</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

<sup>a</sup>Average height AGL for domain extent.
<sup>b</sup>WindNinja horizontal grid resolution depends on the resolution and extent of the digital elevation model used for the simulation.

WRF reanalysis runs were performed using the NCEP North American Regional Reanalysis (NARR) data (Mesinger et al. 2006). The reanalysis runs are referred to as WRF-NARR. The same parameterizations and grid nesting structures used in WRF-UW were also used for the WRF-NARR simulations. Analysis nudging (Deng et al. 2008) was used above the boundary layer in the outermost (36 km) domain of the WRF-NARR simulations. Hourly WRF-NARR simulations were run for 15-day periods with 12 hours of model spin up prior to each simulation.
b. North American Model (NAM)

NAM is an operational forecast model run by NCEP for North America (http://www.emc.ncep.noaa.gov/index.php?branch=NAM). The NAM model uses the NMM core of the WRF model. The NAM CONUS domain investigated in this study has a horizontal grid resolution of 12 km. The NAM model is initialized with 12-hr runs of the NAM Data Assimilation System. It is run four times daily at 00z, 06z, 12z, and 18z and generates hourly forecasts out to 84 hours. NAM forecasts are publicly available in real time from NCEP.

c. High Resolution Rapid Refresh (HRRR)

The HRRR system is an experimental real-time 3-km hourly updated nest inside of the operational 13-km NCEP-Rapid Refresh (RAP) model (http://ruc.noaa.gov/hrrr/). RAP replaced the Rapid Update Cycle (RUC) model as the NOAA next-generation hourly-updated forecast model covering North America in 2012. HRRR uses the ARW core and employs the following physics schemes: Thompson/NCAR microphysics (Thompson et al. 2004), RRTM longwave radiation (Mlawer et al. 1997), Goddard shortwave radiation (Chou and Suarez 1994), MYJ turbulent mixing (Janjic, 2002), and the RUC-Smirnova land-surface model (Smirnova et al. 1997, 2000). HRRR is initialized from 3-km grids with 3-km radar assimilation over a 1-hr period. NCEP intends to provide public access to real-time HRRR forecasts in the near future and HRRR will be the highest resolution operational forecast available to the general public in real time.

d. WindNinja
WindNinja is a mass-conserving diagnostic wind model developed and maintained by the USFS Missoula Fire Sciences Laboratory (Forthofer et al. In Review). WindNinja uses a variational calculus technique to minimize the change in an initial wind field while conserving mass over the computational domain (Forthofer et al. In Review; Forthofer, 2007). It uses a terrain-following coordinate system in which vertical grid resolution is typically on the order of 1 m in the near-surface cells and grows with height above the ground. Typical horizontal grid resolutions are around 100 m for a 50 km × 50 km domain. As with all terrain-following coordinate systems, grid resolution is restricted by skewness in near surface cells in complex terrain; however, due to the lower model top height and finer vertical resolution in the near-surface cells, much finer resolutions can be used in WindNinja than in NWP models.

WindNinja was used to dynamically downscale hourly 10-m wind predictions from the aforementioned NWP models. The WindNinja computational domains were constructed from 30-m digital elevation models. The 10-m NWP winds were bilinearly interpolated to the WindNinja computational domain and used as the initial wind field. Layers above and below the 10-m height were fit to a logarithmic profile. This initial wind field was then adjusted to obtain a flow solution that was mass-consistent but as close (in a least-squares sense) to the initial wind field as possible. An internal diurnal slope flow sub-model (Forthofer et al. 2009) was enabled for these simulations.

3. Evaluations with field observations

a. Field observations

High-resolution surface wind data collected from an isolated mountain (Big Southern Butte, BSB; 43.395958, −113.02257) in southeast Idaho and a steep river canyon (Salmon River
Canyon, SRC; 45.401667, −116.22667) in central Idaho (Wagenbrenner et al. In preparation) were used to evaluate surface wind predictions. BSB is a predominantly grass-covered volcanic cinder cone with a horizontal scale of 5 km and a vertical scale of 800 m and surrounded in all directions by the relatively flat Snake River Plain. The SRC runs east to west, draining high elevation mountains in central Idaho to the Snake River on Idaho’s western border and is surrounded by complex terrain. Surface wind data was collected from a 5-km stretch of the SRC located approximately 20 km upstream from Riggins, Idaho. The canyon walls are predominantly grass-covered and rise roughly 1050 m above the river within this stretch of the SRC. Three-meter wind speeds and directions were measured at 53 and 27 locations at BSB and SRC, respectively. Wind speed and direction data were averaged over a 10-min period at the top of each hour for comparison to hourly NWP forecasts; these observed averages are referred to in the text as hourly winds. Additional details regarding the BSB and SRC field campaigns can be found in Wagenbrenner et al. (In preparation).

b. Case selection and evaluation methods

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. We used the partitioning schemes
described in Wagenbrenner et al. (In preparation) to bin particular observation hours into these three flow regime categories.

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):

\[
\bar{\varphi}' = \frac{1}{N} \sum_{i=1}^{N} \varphi_i'
\]

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

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

where \( \varphi' \) is the difference between simulated and observed variables and \( N \) is the number of observations.

4. Results and discussion
The horizontal grid resolution affects the numerical solution since fewer terrain features can be resolved by coarser grids. Increasing the grid size essentially enforces a terrain smoothing effect, which distorts the actual geometry of the underlying terrain. For example, terrain smoothing causes BSB to appear lower in elevation than it actually is (Fig. 1). As horizontal grid size and terrain complexity increase, the accuracy of the terrain representation, and thus, the accuracy of the near-surface flow solution, deteriorate.
Fig. 1. Terrain representation in WindNinja, WRF-NARR, HRRR, and WRF-UW for the BSB (top panels) and SRC (bottom panels). Surface sensor locations are shown as crosses in the WindNinja image. Scale bars are in km. NAM terrain is represented by just four cells for BSB and one cell for SRC and is not shown here.
a. BSB

i. 5-day simulations

Wind speed predictions improved for all NWP forecasts when downscaled with WindNinja and the largest improvements were for speeds above 10 m s⁻¹ (Fig. 2). Downscaled NAM wind speeds were as accurate as the downscaled HRRR and WRF-UW wind speeds (Fig. 2). This suggests that the NAM forecast was able to capture the important large-scale flow features around BSB, such that the additional resolution provided by HRRR and WRF-UW was not essential to resolve additional flow features in the mean flow around BSB.

This result has important implications, as finer-resolution NWP forecasts require additional computational time compared to coarser-resolution runs for the same domain. Thus, if higher-resolution NWP forecasts do not significantly improve the downscaled forecast, coarser NWP could be used instead, which means less computational time or fewer computing resources would be needed to achieve a forecast of the same skill. The skill of the NAM forecast at BSB is likely due to the fact that Snake River Plain that surrounds BSB is relatively flat and extends at least 50 km in all directions from the butte. Thus, even a 12 km horizontal grid would be capable of resolving the Snake River Plain and diurnal flow patterns within this large, gentle-relief drainage. This result would not be expected to hold in areas of more extensive complex terrain. We show in section b that higher resolution NWP forecasts are necessary to resolve important large-scale flow features induced by the surrounding terrain in order to produce a skillful local wind forecast at the SRC site.
All of the NWP forecasts predicted the overall temporal trend in wind speed correctly (Fig. 3), but tended to underestimate the peak wind speeds, even in the flat terrain on the Snake River Plain (Fig. 4). There was much greater spatial variability in the observed wind speed data than in the NWP predicted speeds (Fig. 3). Wind speeds varied across the domain by up to 18 m s\(^{-1}\) during high-wind periods due to mechanically-induced effects of the terrain on the flow. The highest speeds occurred on upper elevation windward slopes and ridgetops and the lowest on the leeward side of the butte and in sheltered side drainages on the butte itself (Wagenbrenner et al. In preparation).

The coarser resolution forecasts predicted the least amount of spatial variability in wind speed. This is because there were fewer grid cells covering the domain for the coarser resolution models, and thus fewer prediction points around the butte. The spatial variability in the
downscaled wind speed predictions more closely matched that of the observed data (Fig. 3 and 4), although highest speeds are still under-predicted. Downscaling generally improved the spatial variability of the predictions; however, there were cases where NWP errors clearly propagated into the downscaled simulations. For example, HRRR consistently over-predicted morning wind speeds and this error was amplified in the downscaled WindNinja simulations (Fig. 3 and 5).

The mean bias, rmse, and sde for wind speed and wind direction were all lower for the downscaled simulations than for the NWP forecasts during the five-day period (Table 2). Mean biases in wind speeds were all slightly negative and NAM and WRF-UW (the two coarsest NWP forecasts) had the largest mean biases. The rmse and sde in wind speed were largest for HRRR, however. Although mean bias, rmse, and sde in wind direction for the downscaled forecasts were smaller or equal to those for the NWP forecasts, the differences were small, with a maximum reduction in mean bias in wind direction of just 4°.
Fig. 3. Observed (black) and predicted (colored) winds speeds for 15 July 2010–19 July 2010 at BSB. Top panels are WindNinja predictions. Bottom panels are NWP predictions.
Fig. 4. Observed (black line) and predicted (colored lines) wind speeds for R2 located 5 km southwest of BSB on the Snake River Plain. Solid color lines are NWP and dashed color lines are WindNinja.
Fig. 5. Observed (black) and predicted (colored) winds speeds for 18 July 2010 at BSB. Top panels are WindNinja predictions. Bottom panels are NWP predictions.
Table 2. Model mean bias, root-mean-square error (rmse), and standard deviation of errors (sde) for surface wind speeds and directions at BSB.

<table>
<thead>
<tr>
<th>Time period</th>
<th>Statistic</th>
<th>NWP model alone</th>
<th>Downscaled with WindNinja</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NAM</td>
<td>WRF-</td>
</tr>
<tr>
<td></td>
<td>Wind Speed (m s(^{-1}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-day</td>
<td>Bias</td>
<td>-0.84</td>
<td>-1.17</td>
</tr>
<tr>
<td></td>
<td>Rmse</td>
<td>2.15</td>
<td>2.08</td>
</tr>
<tr>
<td>5-day</td>
<td>Sde</td>
<td>2.15</td>
<td>2.08</td>
</tr>
<tr>
<td>Downslope</td>
<td>Bias</td>
<td>-1.07</td>
<td>-1.15</td>
</tr>
<tr>
<td></td>
<td>Rmse</td>
<td>1.79</td>
<td>1.67</td>
</tr>
<tr>
<td></td>
<td>Sde</td>
<td>1.79</td>
<td>1.67</td>
</tr>
<tr>
<td>Upslope</td>
<td>Bias</td>
<td>-0.81</td>
<td>-1.11</td>
</tr>
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<td></td>
<td>Rmse</td>
<td>1.52</td>
<td>1.69</td>
</tr>
<tr>
<td></td>
<td>Sde</td>
<td>1.52</td>
<td>1.69</td>
</tr>
<tr>
<td>Synoptically-driven</td>
<td>Bias</td>
<td>-0.57</td>
<td>-1.28</td>
</tr>
<tr>
<td></td>
<td>Rmse</td>
<td>3.00</td>
<td>2.94</td>
</tr>
<tr>
<td></td>
<td>Sde</td>
<td>3.00</td>
<td>2.94</td>
</tr>
<tr>
<td></td>
<td>Wind Direction (°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-day</td>
<td>Bias</td>
<td>59</td>
<td>57</td>
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<tr>
<td></td>
<td>Rmse</td>
<td>76</td>
<td>74</td>
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<tr>
<td></td>
<td>Sde</td>
<td>47</td>
<td>47</td>
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<tr>
<td>Downslope</td>
<td>Bias</td>
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<td>61</td>
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<tr>
<td>Upslope</td>
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</table>
|             | Sde       | 43    | 44    | 45    | 43    | 44    | 47    | 44    | 46    | 43    | 44    | 45    | 43    | 44    | 47    | 44    | 46    | 45


**ii. Upslope, downslope, and synoptically-forced flows**

The biggest improvements from downscaling occurred during synoptically-driven flow events (Fig. 6). This is not surprising, since the highest spatial variability in the observed wind speeds occurred during high-wind events due to the mechanically-induced effects of the terrain. It is during these events that the downscaling has the most opportunity to improve predictions across the domain. There were consistent improvements in predicted wind speeds during the upslope regime, although the improvements were smaller than for the synoptically-driven regime. Wind speeds improved for WRF-UW and NAM, but not for WRF-NARR or HRRR during the downslope regime. Wind directions improved with downscaling for all models during the downslope regime and for all but HRRR during the upslope regime. Improvements in the downslope and upslope regimes are due at least in part to the effects of diurnal algorithm within WindNinja. Consistent improvements in wind directions suggest that the diurnal slope flow model is helping under these flow conditions.
Fig. 6. Root mean squared error in wind speed (left) and wind direction (right) at BSB for the entire five-day evaluation period ($N = 6360$) and downslope ($N = 2650$), upslope ($N = 1113$), and synoptically-driven ($N = 1325$) periods within the five-day period. Sample size, $N =$ number of hours x number of sensor locations.

b. SRC

i. 5-day simulations

Wind speed predictions were improved with downscaling for the two highest resolution NWP models, WRF-NARR and HRRR for observed speeds above 3 m s$^{-1}$ (Fig. 2). The WRF-UW and NAM wind speed forecasts were not improved with downscaling (Fig. 2). This is possibly because the coarser grids used by WRF-UW and NAM do not resolve the Salmon River drainage and surrounding terrain in enough detail to capture canyon-scale flow effects important to the local flows in the SRC study area. This point is discussed further below. As with the BSB simulations, the spatial variability in the NWP wind speed predictions was too low at SRC (Fig. 7). The spatial variability in downscaled predictions more closely matched the spatial variability
in the observed data, although the downscaled predictions tended to over-predict the peak wind speeds.
Fig. 7. Observed (black) and predicted (colored) winds speeds for 15 August 2011–19 August 2011 at SRC. Top panels are WindNinja predictions. Bottom panels are NWP predictions.
Fig. 8. Observed (black) and predicted (colored) winds speeds for 16 August 2011 at SRC. Top panels are WindNinja predictions. Bottom panels are NWP predictions.
The five-day period included two days (August 16 and 17) of very strong down-drainage flows enhanced by the presence of an east-west surface pressure gradient in the region (discussed in Wagenbrenner et al. In preparation). These pressure-driven flow events are not predicted by NAM or WRF-UW because the domains used in these models do not resolve the river canyon at all (Fig. 1). The 12-km and 4-km grid resolutions used by these models are too coarse to resolve a structure that is ~1km wide. The east-west scale of the river canyon, however, is 100’s of km and the canyon-scale winds induced from thermally driven down-drainage winds and enhanced by an east-west surface pressure-gradient in the region are sufficiently strong to decouple the near-surface river canyon flows from the large-scale flows aloft.

Because of the inability of the NAM and WRF-UW to resolve the Salmon River drainage, these models completely missed the morning high winds associated with pressure-driven easterly flow events (Fig. 7 and 8). WRF-NARR and HRRR predicted small peaks in morning winds, although the magnitudes were too small and timing appeared to be slightly off (Fig. 7 and 8). The fact that these models predicted a peak at all in the morning winds was likely due to the fact that these simulations were able to at least partially resolve the river canyon. The WRF-NARR (1.33 km resolution) wind field appeared to capture the down-drainage flow event on August 16 2011 (Fig. 9). This is evidenced by the easterly oriented vectors in the vicinity of the Salmon River. The WRF-UW (4 km resolution) wind field, however, did not appear to be influenced by the river canyon. In order to predict local winds during these types of pressure-driven down-drainage events, a NWP model resolution of at least 3 km and possibly 1.33 km is necessary to resolve important large-scale flow features.
The mean bias, rmse, and sde in wind speeds were not improved with downscaling for any of the NWP models (Table 3). This is not surprising for the NAM and WRF-UW simulations since we have already shown that these models were not able to capture important large-scale features in the flow induced by surrounding complex terrain. Since WindNinja attempts to minimize the change from the initial flow field while enforcing conservation of mass, any large errors in the mean flow field for the domain would be likely to propagate through to the downscaled predictions. Thus, the skill of the WindNinja forecast will always be constrained by the accuracy of the initial mean flow field for the domain. For a region with highly complex terrain, such as the SRC, the ‘mean flow field’ becomes more difficult to describe and thus more difficult to prescribe as an initial condition. For example, a single NWP point for BSB may have been enough to describe the mean flow and achieve benefits from downscaling. In more complex terrain, such as at SRC, several NWP predictions may be needed to appropriately describe the mean flow in order to achieve the same benefits from downscaling.

The mean bias, rmse, and sde in wind direction were lower for all downscaled simulations (Table 3, Fig. 10). Improvements in the predicted wind directions could be
beneficial even if the wind speed predictions are not improved. Improved wind directions suggest that at least the terrain-channeling effects are being captured appropriately to reorient the wind vectors in a manner consistent with the local terrain features. This improvement would be important for fire spread modeling, for example, where surface wind direction is one of the driving factors controlling the direction of fire propagation.
Table 3. Model mean bias, root-mean-square error (rmse), and standard deviation of errors (sde) for surface wind speeds and directions at SRC.

<table>
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<tr>
<th>Time period</th>
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<th>Wind Speed (m s(^{-1}))</th>
<th>NWP model alone</th>
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ii. Upslope, downslope, and synoptically-forced flows

The only improvements in wind speed occurred during periods of synoptically-driven flow. It is possible that the consistent over-predictions in the downscaled wind speeds is due to a parameterization in the diurnal slope flow model used in WindNinja and this should be further investigated. Wind direction was improved for all flow regimes and all NWP models by downscaling. A consistent improvement in wind direction suggests that the diurnal slope flow algorithm helped to orient the flow during periods of downslope and upslope regimes. Improvements in wind direction during the synoptically-driven flow regime are likely due to the better terrain representation in WindNinja.

Fig. 10. Root mean squared error in wind speed (left) and wind direction (right) at SRC for the entire five-day evaluation period ($N = 3240$) and downslope ($N = 1161$), upslope ($N = 783$), and synoptically-driven ($N = 405$) periods within the five-day period. Sample size, $N =$ number of hours x number of sensor locations.
5. Conclusions

Wind predictions at BSB were improved for all NWP models by downscaling with WindNinja. The largest 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 and HRRR wind speeds at BSB. HRRR and WRF-NARR wind predictions were improved by downscaling with WindNinja for observed wind speeds above 3 m s\(^{-1}\). 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. Consistent over-prediction in speeds 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 other model applications that are sensitive to surface wind fields, such as fire behavior, transport and dispersion, and wind energy applications.
6. Acknowledgements

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CHAPTER FOUR

WIND EROSION FROM A SAGEBRUSH STEPPE BURNED BY WILDFIRE:
MEASUREMENTS OF PM10 AND TOTAL HORIZONTAL SEDIMENT FLUX

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erosion from a sagebrush steppe burned by wildfire: measurements of PM10 and total horizontal
Abstract

Wind erosion and aeolian transport processes are under studied in the post-wildfire environment compared to rainfall-induced erosion and sediment transport on burned landscapes. Post-fire wind erosion studies have predominantly focused on near-surface sediment transport and associated impacts such as on-site soil loss and site fertility. Downwind impacts, including air quality degradation and deposition of dust or contaminants, are also likely post-fire effects; however, quantitative field measurements of post-fire dust emissions are needed for assessment of these downwind risks. A wind erosion monitoring system was installed immediately following a desert sagebrush and grass wildfire in southeastern Idaho, USA to measure wind erosion from the burned landscape. This paper describes findings related to horizontal sediment flux and PM$_{10}$ emissions from the burned area. We determined threshold wind speeds and corresponding threshold friction velocities to be 6.0 and 0.20 m s$^{-1}$, respectively, for the four months immediately following the fire and 10 and 0.55 m s$^{-1}$ for the following spring months. Several major wind erosion events were measured in the months following the July 2010 Jefferson Fire. The largest wind erosion event occurred in early September 2010 and produced 1495 kg m$^{-1}$ of horizontal sediment transport within the first two meters above the soil surface, had a maximum PM$_{10}$ vertical flux of 32.3 mg m$^{-3}$ s$^{-1}$, and generated a large dust plume that was visible in satellite imagery. The peak PM$_{10}$ concentration measured on-site at a height of 2 m in the downwind portion of the burned area was 690 mg m$^{-3}$. Our results indicate that wildfire can convert a relatively stable landscape into one that is a major dust source.
1. **Introduction**

Wind erosion and aeolian sediment transport processes are under unstudied compared to rainfall-induced soil erosion and fluvial sediment transport in post-wildfire environments. Recent work suggests that wind erosion can play a major role in burned landscapes (Ravi et al., 2007). Burned soils are susceptible to particle entrainment by wind because fire consumes protective ground cover, soil organic matter, and soil-stabilizing root networks, and can destroy naturally occurring soil crusts (Ford and Johnson, 2006), induce soil water repellency (Ravi et al., 2007), and decrease aggregate stability (Varela et al., 2010), all of which increase the wind erodibility of the soil. It will be increasingly important to understand the links between fire and post-fire wind erosion as the occurrence of wildfire is projected to increase for much of the western US in future decades due to climate change and expansion of the wildland urban interface (Flannigan et al., 2009; Theobald and Romme, 2007).

This paper presents an overview of wind erosion measured from soils burned by the 2010 Jefferson Fire on the Snake River Plain of southeastern Idaho, USA. Strong pulses of aeolian sediment transport have been reported following wildfires in this region (Sankey et al., 2009a), removing up to 5 cm of surface soil in the months following wildfire (Sankey et al., 2010) and resulting in substantial losses of soil nutrients (Hasselquist et al., 2011; Sankey et al., 2012). Fires tend to occur during the warm, dry summer period and vegetation recovery typically does not occur until the subsequent spring or summer, leaving months of bare soil exposure in which erosion varies with soil moisture and sediment supply (Sankey et al., 2009b; Sankey et al. 2012). Wind erosion does not occur or is insignificant until sites are burned in this region, and burned sites thus generate relatively high amounts of fine sediment and organic matter (Hasselquist et al., 2011) that would seem to poise newly burned sites for relatively large dust emissions.
Blowing dust and ash from burned areas can impact visibility, air quality, soil productivity and nutrient transport (Whicker et al., 2006), and deposition of wind-blown dust and ash can have implications for water quality (Vicars et al., 2010) and snowmelt processes (Painter et al., 2010; Rhodes et al., 2010). Additionally, contamination of croplands due to deposition of herbicide-treated soils from post-fire areas is a concern (e.g., High Country News, Issue 228, 2002).

The overall goal of this research is to quantify the role of wind erosion and corresponding impacts on air quality from the 2010 Jefferson Fire. Specific objectives were to (1) collect time-resolved measurements of horizontal sediment flux and PM$_{10}$ vertical flux following the wildfire and (2) present these measurements in the context of surface and meteorological parameters including wind speed, friction velocity, relative humidity, soil moisture, solar radiation, air temperature, and ground cover. This study reports some of the first measurements of PM$_{10}$ emissions from burned soils and provides a relatively comprehensive assessment of wind erosion from a post-fire environment, in terms of the modes of sediment transport monitored. We provide an overview of data collected over the 11-month monitoring period and then detail four specific wind erosion events, two in the fall following the fire and two that occurred the following spring after the snowmelt. Horizontal sediment flux is important for estimating on-site soil redistribution and associated effects, while the PM$_{10}$ vertical flux impacts downwind air quality. The data collected during this study demonstrate the significant role that wind erosion can play in the broader environment downwind from burned sites.

2. Methods

2.1 Site Description
The Jefferson Fire burned 44,110 ha of semi-arid sagebrush steppe in southeastern Idaho, USA (43°40’N, 112°35’W, elevation 1500 m) during July 2010. The fire followed a northeast trajectory and burned a strip of land nearly 50 km long and 8 km wide (Fig. 1). Wind erosion monitoring equipment was installed in the downwind (northeast) portion of the burned area roughly two weeks after the fire was contained. The length of the area burned upwind of the monitoring equipment was 45 km (Fig. 2).
Fig. 1. Location and extent of the area burned by the Jefferson Fire. Image courtesy of Google Earth.
Fig. 2. Instrumentation installed at the site.

Average precipitation at the site is 280 mm yr\(^{-1}\) and prevailing winds are from the southwest (NRCS Web Soil Survey). Soil depth ranges from 0 to greater than 200 cm and surface soils in this region are predominantly loamy sands with up to 20 percent of the burned area covered by stony outcroppings of fractured basalt bedrock (NRCS Web Soil Survey). Soil surfaces directly upwind of the monitoring location were predominately loams with less than 20 percent rock outcroppings. Unburned soils in this ecosystem are typically protected by a naturally occurring soil crust and natural wind erosion rates are low, with an average horizontal
sediment flux of 0.0003 g m$^{-1}$ day$^{-1}$ (Sankey et al., 2009a). The terrain is relatively flat with slopes ranging from 2 to 20 percent. Pre-fire vegetation was comprised primarily of Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingenis* Rydb.) and bluebunch wheatgrass (*Agropyron spicatum* Pursh.). The fire consumed nearly all of the vegetation, leaving only the exposed root bases of the sagebrush (Fig. 3).

![Fig. 3. Pre-fire (left) and post-fire (right) vegetation at the study site.](image)

There was essentially no human-caused disturbance in the burned area upwind of our monitoring equipment during the study. There were a few unpaved roads located within the burn perimeter, but these were located on Idaho National Engineering Laboratory land and access was tightly restricted. There was little to no traffic on these roads during our study period. The access road we used was on BLM land about 1 km northeast (downwind) of the monitoring equipment. We accessed the site by foot from this road. The fire was contained along a county road just northeast of this access road and along Interstate-15 (both were downwind of the monitoring equipment). No fire containment lines were constructed upwind of the monitoring equipment.
2.2. Measurements

We measured horizontal sediment flux and PM$_{10}$ concentration gradients for 11 months following the fire containment in late July 2010. Horizontal sediment flux was measured at three locations along a 50-m transect normal to the prevailing wind direction using BSNE passive sediment collectors (Custom Products and Consulting, Big Spring, TX) with inlets at 5, 10, 20, 55, and 100 cm above the soil surface. The BSNE traps were located in close proximity to the PM$_{10}$ sensors to insure that the measured PM$_{10}$ and total horizontal sediment flux was representative of the same topography, soil conditions, and meteorological conditions. Sediment was collected from the BSNE traps roughly every two weeks and oven dried at 105 °C and weighed to determine sediment mass fluxes. Inlet heights were re-measured twice following substantial deflations of the soil surface elevation. PM$_{10}$ concentration gradients were measured at two locations along the same transect as the BSNE traps using E-Sampler Particulate Sensors (MetOne Instruments, Grants Pass, OR). Real-time (5-min average) PM$_{10}$ concentrations were monitored at 2 and 5-m heights at each location. We use the term ‘peak concentration’ to refer to a peak 5-min average concentration over larger time scales. E-Sampler PM$_{10}$ concentrations were calibrated against concentration readings from a Beta Attenuation Monitor (E-BAM 1020, MetOne Instruments, Grants Pass, OR), which is a US EPA approved method for monitoring ambient PM$_{10}$ concentrations (Automated Equivalent Method: EQPM-0798-122; US EPA, 2011). The calibration was performed based on laboratory wind tunnel tests in which a steady stream of burned surface soil from the study site was introduced into the tunnel and PM$_{10}$ was measured downwind. Soil feed rates were chosen to produce PM$_{10}$ concentrations ranging from 1 to 30 mg m$^{-3}$ (as measured by the E-BAM). This calibration range was determined based on
the capabilities of the soil feed system in our wind tunnel test chamber. Three two-minute calibration tests were performed for each sampler at each concentration.

Mean winds, temperature, and turbulence were monitored with a CSAT3 sonic anemometer (Campbell Scientific, Logan, UT) operated at 10 Hz at a height of 5 m. Wind speeds were also measured with two cup-and-vane anemometers 2-m above the ground (model 014-A, Met-One, Grants Pass, OR). Hourly relative humidity, solar radiation, precipitation, soil temperature, and soil moisture were also monitored throughout the study period. Ground cover was measured monthly during the study period at six locations along two transects which began at the monitoring site and extended 100 m to the southwest. Percent ground cover was estimated for 1-m² plots (Fig. 4) at each location using a grid point-count method similar to methods described in Booth et al. (2005).
Fig. 4. Time series photos of a single ground cover plot.

Vertical flux of PM$_{10}$ was calculated as

\[ F_v = \frac{ku_*(C_1 - C_2)}{\ln \left( \frac{z_2}{z_1} \right)} \]  \hspace{1cm} (1)
Where \( k \) is the von Karman constant, \( u^* \) is friction velocity, and \( C_1 \) and \( C_2 \) are PM\(_{10}\) concentrations at heights \( z_1 \) and \( z_2 \), respectively. This calculation assumes neutral atmospheric stability and is appropriate for the strong wind conditions that produce measurable dust fluxes. Some of the dust events measured during this study produced sufficiently large horizontal sediment fluxes to obscure the PM\(_{10}\) concentration gradient between the 2- and 5-m measurement heights. Measurement of this concentration gradient is necessary to calculate the vertical flux based on gradient transport theory, which is the basis of Eq (1). In order to mitigate this issue and provide more reasonable estimates of PM\(_{10}\) vertical flux, we estimated PM\(_{10}\) concentrations at a height of 10 m based on a Gaussian vertical profile. The Gaussian profile is described by

\[
C = C_0 \exp\left( - \frac{(H - h)^2}{2\sigma_z} \right)
\]  

(2)

where \( C \) is the concentration at height \( H \) above ground, \( C_0 \) is the peak concentration in the Gaussian distribution curve, \( h \) is the height above ground where \( C_0 \) occurs (\( h \) is 0 for this case since the ground surface is the source), and \( \sigma_z \) is the coefficient for vertical dispersion. We estimated \( C_0 \) from Eq (2) based on the measured concentrations at 5 m. We then used Eq (2) with the estimated ground-level concentrations, \( C_0 \), to calculate \( C \) at a height, \( H \), of 10 m. We assumed \( \sigma_z = 3 \) as a reasonable estimate of the vertical dispersion coefficient for neutral atmospheric stability (e.g., Bowne, 1974). The reported PM\(_{10}\) vertical fluxes are those calculated based on the concentration gradient between 5 m and the extrapolated concentration at 10 m. For completeness, PM\(_{10}\) vertical fluxes calculated from both methods (measurements at 2 and 5 m and measurements at 2 m and 10 m) are reported in Figure 6.
Horizontal sediment flux was determined for each two-week sampling interval by fitting the vertical distribution of soil mass caught by the BSNE collectors to a power function of the form

\[ Q = az^{-b} \]  \hspace{1cm} (3)

Where \( Q \) is the mass of sediment caught per unit width at each height, \( z \), and \( a \) and \( b \) are fitted parameters. Model fits had \( r^2 > 0.995 \) in all cases except on 7 September 2010, when \( r^2 = 0.85 \), due to saturation (or near-saturation) of some collectors (4 of the 15 collectors). Heights were updated to match the deflating soil surface, and the power function was integrated over 0 to 2 m to calculate horizontal sediment flux for each BSNE tower. Our highest BSNE inlet was 1 m above the soil surface; however, we know that sediment transport occurred above this 1-m height. Thus, we chose to integrate the derived power function to a height of 2 m in order to calculate the majority of horizontal sediment transport. The 2-m height was chosen as an appropriate cutoff because horizontal sediment flux decreases rapidly with height above the soil surface. This approach has been used in other studies (e.g., vanDonk et al., 2003). Organic matter was not removed from the BSNE-collected soils prior to analysis. There was relatively little organic material in the BSNE traps and because the density of the organic particles is much less than that of the mineral soil, the contribution of organic matter to the total mass of the sediment in the BSNE traps was negligible.

A particle size analysis was performed on the BSNE-collected sediment with a Mastersizer particle analyzer (Malvern Instruments). The particle analyzer uses laser diffraction to determine the percentage of particles within discrete size bins ranging from 0.05 to 800 \( \mu \)m in
diameter. Particle size analyses were only performed on BSNE sediment collected during three of the fall 2010 sampling periods due to equipment availability. Three replicates were performed on each BSNE bin and averaged within the bin and across the three BSNE towers to get an average particle size distribution per BSNE bin height.

We present the calculated horizontal sediment fluxes in two forms: (1) as the total flux during the sampling interval (usually about 2 weeks) and (2) as the average horizontal sediment flux on a per minute basis that is adjusted to include only periods when erosion was occurring. The PM$_{10}$ data were used to determine threshold wind speeds for the fall 2010 and spring 2011 monitoring periods. We determined periods of wind erosion to be those periods when wind speeds were above the threshold wind speed for PM$_{10}$ emissions. Presenting the flux measurements in these two forms allows the reader to (1) see the value we directly measured, total flux for the sampling period, and also (2) more easily compare the horizontal sediment flux to the PM$_{10}$ vertical flux. Reporting the horizontal sediment flux averaged over only periods of wind erosion gives a better estimate of the ratio of PM$_{10}$ vertical flux to horizontal sediment flux.

We calculated the ratio of PM$_{10}$ vertical flux to horizontal sediment flux to provide an indication of the amount of PM$_{10}$ emitted from the horizontal transport. There appear to be two conventions for reporting this ratio in the literature. One convention is to report the ratio with units of m$^{-1}$, which are the units that result from dividing PM$_{10}$ vertical flux by horizontal sediment flux. In order to get a true ratio (i.e., dimensionless), the fetch length contributing the BSNE measurements has to be accounted for. PM$_{10}$ vertical flux is the flux through a plane parallel to the earth’s surface. Horizontal sediment flux is the flux through a plane normal to the earth’s surface. In other words, there is a footprint associated with the PM$_{10}$ vertical flux and so the length dimension (the fetch) contributing to the horizontal sediment flux needs to be included.
in the calculation to account for the footprint of the BSNE measurement. We did not measure this fetch distance in our study and there does not appear to be a clear method for estimating this value in the literature. Hagen et al. (2010) reported a 250 m fetch length to reach sediment transport capacity for agricultural soils. Attempts to use this fetch distance in our study resulted in ratios that appeared to be unreasonably high (> 40%) and so we report the ratio of vertical flux to horizontal transport without adjusting for a contributing fetch distance.

3. Results

Winds were predominantly from the southwest with maximum speeds of up to 19 m s\(^{-1}\) during this study. Winds of up to 8 m s\(^{-1}\) were also recorded from the northeast (Fig. 5). The months following the fire were relatively dry with only 82 mm of rainfall between 1 August and 3 November 2010 (Fig. 5). There was snow on the ground at the site from mid-November 2010 to late March 2011 and data were not collected during this period. The spring season was slightly wetter than the fall, with 140 mm of rainfall between 5 May and 12 July 2011 (Fig. 5). The fire consumed essentially all of the vegetation. Rock and burned roots covered 11% of the ground area immediately following the fire, leaving 89% of the area as exposed bare soil. There was no vegetation re-growth between August 2010 and March 2011. Vegetation began to reemerge in late April and by mid-June comprised 6% of the ground cover on site. Post-fire vegetation within a distance of 500 m upwind of the monitoring equipment was comprised of exotic annual halogeton (Halodegeton glomerata) and native rabbit brush (Chrysothamnus nasseousa). Total ground cover increased to 17% (rock, roots, and live vegetation) in July 2011 (Fig. 3).
Figure 5. Overview of post-fire meteorology and sediment transport from 10 August 2010 to 16 July 2011. PM$_{10}$ concentrations are 5-min averages measured at 2 m above the soil surface. Horizontal sediment flux is the flux within a 2 m height above the soil surface; bars represent the total horizontal sediment flux for the sampling interval.
PM$_{10}$ vertical fluxes calculated based on concentration gradients between 2 and 5 m and 5 and 10 m are shown in Fig. 6. The vertical fluxes based on the concentration gradient between 2 and 5 m appear to be unreasonable as the vertical fluxes are larger in the spring than in the fall, although measured PM$_{10}$ concentrations are lower in the spring than in the fall and friction velocities are comparable (Fig. 6; Fig. 7). This apparent increase in the spring vertical flux values was likely due to underestimation of the fall vertical flux values. We suspect that the fall vertical flux values were underestimated due to the large amount of horizontal sediment transport within the surface layer which obscured the concentration gradient between the 2- and 5-m heights. Accurate measurement of the concentration gradient is necessary in order to calculate the vertical flux using Eq (1). The calculated vertical fluxes based on the concentration gradient between 5 and 10 m appear to be more reasonable estimates and thus are the values reported in the remainder of this text.
The largest wind erosion events occurred during the two months following the fire (early September 2010) during periods of high winds and relatively dry conditions (Fig. 5). Horizontal sediment flux and PM$_{10}$ emissions peaked during a large wind event in early September. Horizontal sediment flux and PM$_{10}$ vertical flux decreased between mid-September and mid-October 2010 due to less frequent high-wind events and more frequent rainfall. Horizontal sediment flux increased again during a strong wind event in late October 2010 after a break in rainfall and before the snow cover arrived; we measured 0.34 kg m$^{-1}$ min$^{-1}$ of horizontal sediment flux during the PM$_{10}$ emission episodes over the two-week period ending on 1 November 2010.
(640 kg m\(^{-1}\) total over the 2-week period); horizontal sediment flux during this period was larger than the pre-September horizontal sediment fluxes measured in the weeks following the fire (Fig. 5). Several wind erosion events occurred following the spring snowmelt and prior to significant rainfall and vegetation re-growth. Horizontal sediment flux and PM\(_{10}\) emissions decreased from May through July 2011 as vegetation began to recover at the site.

Results from the particle size analyses showed that on average 5.3% (range of 3.2 to 7.5%) of the horizontal sediment flux was PM\(_{10}\) and 60% (range of 55.4 to 68.5) of the PM\(_{10}\) fraction was PM\(_{2.5}\). The fraction of PM\(_{10}\) was relatively constant between the 29 July 2010 sample (5.9%) and the 7 September 2010 collection (6.2%), but decreased slightly during the 18 November 2010 collection (3.9%). The PM\(_{2.5}\) fraction of the PM\(_{10}\) remained constant throughout the fall monitoring period. Particle size analyses were not performed on the spring 2011 BSNE-collected sediment due to instrument availability.

Threshold 2-m wind speeds were determined to be 6 m s\(^{-1}\) and 10 m s\(^{-1}\) during the fall 2010 and spring 2011 monitoring periods, respectively. Corresponding threshold friction velocities were 0.20 and 0.55 m s\(^{-1}\). These wind speeds are frequently experienced on the Snake River Plain, which is considered to be an environment of modest to high wind energy (Jewell and Nicoll, 2011). The total number of minutes of PM\(_{10}\) emissions was determined based on the amount of time above the threshold wind speed. We estimated a total of 381 hours of PM\(_{10}\) emissions over the course of 62 wind events during this field campaign. The measured peak PM\(_{10}\) concentrations during the September 2010 wind event exceeded the range of E-Sampler specifications (0-100 mg m\(^{-3}\)). The E-Sampler results did not appear to be saturated at concentrations above the certified range (i.e., the concentration readings did not plateau at an upper limit). We applied the same calibration to concentrations above this range as we did to
those within the range; no additional adjustments were made. This is a limitation of the sensor and we are not aware of other PM$_{10}$ sensors with the capability of measuring the high concentrations observed during the largest dust events at this site.

The largest calculated maximum and storm average PM$_{10}$ vertical fluxes during this campaign were 32.3 mg m$^{-2}$ s$^{-1}$ and 6.47 mg m$^{-2}$ s$^{-1}$, respectively. Ratios of PM$_{10}$ vertical flux to horizontal sediment flux ranged from < 0.0001 to 0.015 m$^{-1}$.

Table 1. Calculated PM$_{10}$ vertical fluxes, horizontal sediment fluxes, and ratios of PM$_{10}$ vertical flux to horizontal sediment flux for four wind erosion events.

<table>
<thead>
<tr>
<th>Event</th>
<th>Duration (hr)</th>
<th>$F_v$ (mg m$^{-2}$ s$^{-1}$)</th>
<th>$Q$ (kg m$^{-3}$ min$^{-1}$)</th>
<th>$F_v/Q$ (m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-5 Sep 2010</td>
<td>28.5</td>
<td>Max: 32.3, Avg: 5.34</td>
<td>0.20</td>
<td>Max: 0.0097, Avg: 0.0016</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-4 Oct 2010</td>
<td>4.5</td>
<td>Max: 4.28, Avg: 0.58</td>
<td>0.06</td>
<td>Max: 0.0150, Avg: 0.0019</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 Apr 2011</td>
<td>8.0</td>
<td>Max: 15.9, Avg: 2.21</td>
<td>0.09</td>
<td>Max: 0.0025, Avg: 0.0003</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 Jun 2011</td>
<td>7.0</td>
<td>Max: 2.05, Avg: 0.54</td>
<td>0.06</td>
<td>Max: 0.0001, &lt; 0.001</td>
</tr>
</tbody>
</table>

$F_v$ is vertical flux of PM$_{10}$. $Q$ is horizontal sediment flux.
Figure 7. Observed wind speed, wind direction, friction velocity, and PM$_{10}$ concentration for specific wind erosion events. PM$_{10}$ concentrations were only measured at the 2-m height during the September 2010 event. Vectors indicate wind direction (arrow pointing to the right indicates wind from the west) and speed (magnitude of the vector). Note changes in the scale of the y-axes.

3.1. Specific events

The largest horizontal sediment flux and highest PM$_{10}$ vertical flux were measured during the strongest wind event of this field campaign in early September 2010, roughly seven weeks after the fire. The wind event occurred during the passage of a frontal system that brought sustained daytime winds of up to 19 m s$^{-1}$ and nighttime wind speeds of 6 m s$^{-1}$ (Fig. 7). The
frequency and importance of these types of frontal systems for driving dust emissions in the Great Basin region of the western U.S. has been previously reported (Hahnenberger and Nicoll, In press). Early morning winds were from the northeast and stronger mid-day winds were from the southwest. The horizontal sediment flux measured during the 13-day BSNE sampling period that included this event was 1495 kg m\(^{-1}\) and 0.2 kg m\(^{-1}\) min\(^{-1}\) during the PM\(_{10}\) emission periods. Real-time PM\(_{10}\) concentrations followed trends in wind speed and friction velocity, and a peak concentration of 690 mg m\(^{-3}\) (Fig. 7) was measured on 4 September 2010 at 17:30. Calculated maximum PM\(_{10}\) vertical fluxes during the two distinct peaks shown in Fig. 6 were 30.2 and 32.3 mg m\(^{2}\) s\(^{-1}\). PM\(_{10}\) concentrations were slightly higher on 4 September than on 5 September, although observed wind speed was not notably different between the two days. A possible explanation that may account for the difference in PM\(_{10}\) concentrations between days was the slight shift in wind direction between days; winds were slightly more from the west on 4 September. The change in wind direction may have influenced PM\(_{10}\) concentrations at the sampling towers if the area to the west was more erodible than the area to the southwest. Another possibility is that the supply of erodible surface material was depleted during 4 September and consequently there was less material available for entrainment on 5 September.

A large dust plume originating from the burned area on 5 September 2010 was visible in MODIS satellite imagery and extended at least 100 km downwind of the source area (Fig. 8). The dust plume visible in the MODIS imagery clearly followed the mid-day southwest wind trajectory.
Another event occurred in early October 2010 when nighttime southerly winds increased to 6 m s\(^{-1}\) just before midnight on 3 October 2010 (Fig. 7). This event was smaller than the early September 2010 event and rather than producing sustained PM\(_{10}\) emissions as with the September frontal event, the October event included a series of spikes in wind speed and PM\(_{10}\) concentrations over the span of several hours. Horizontal sediment flux for the two-week period that included this event was 120.4 kg m\(^{-1}\) or 0.6 kg m\(^{-1}\) min\(^{-1}\) during the PM\(_{10}\) emission periods. The largest spike in PM\(_{10}\) emissions occurred at midnight on 3 October when wind speed increased from around 7 to 14 m s\(^{-1}\) for about 10 minutes and PM\(_{10}\) concentrations peaked at 40.1 mg m\(^{-3}\). Calculated maximum PM\(_{10}\) vertical fluxes during the three distinct peaks in October 2010 shown in Fig. 6 were 15.0, 2.76, and 2.63 mg m\(^{-2}\) s\(^{-1}\). This event was notable since it occurred during nighttime conditions and had several distinct spikes in PM\(_{10}\) emissions. The spikes in PM\(_{10}\) were coincident with spikes in wind speed and demonstrate the sensitivity of the burned soils to fluctuations in wind speed.
We observed the first wind erosion event of the spring monitoring period on 28 April 2011. This event occurred during the passage of a frontal system that brought sustained southwesterly mid-day winds of 12 to 14 m s\(^{-1}\) (Fig. 7). The horizontal sediment flux for the 9-day BSNE sample period that included this storm was 136.8 kg m\(^{-1}\) or 0.09 kg m\(^{-1}\) min\(^{-1}\) during the PM\(_{10}\) emission periods. PM\(_{10}\) emissions began to pick up around 10:00 when wind speeds reached 12 m s\(^{-1}\). There were two distinct peaks in PM\(_{10}\) concentrations, one around 15:00 when the wind speed reached 13 m s\(^{-1}\) and the PM\(_{10}\) concentration reached 35.7 mg m\(^{-3}\) at the 2-m height, and another larger one around 19:00 when the wind speed reached 14 m s\(^{-1}\) and the PM\(_{10}\) concentration at 2 m peaked at 50 mg m\(^{-3}\). The maximum PM\(_{10}\) vertical fluxes during the two peaks were 3.68 and 1.49 mg m\(^{-2}\) s\(^{-1}\).

Wind erosion tapered off by June 2011 despite frequent high-wind events. A wind event in mid-June produced a much smaller horizontal sediment flux and lower PM\(_{10}\) vertical flux than previous wind events of similar magnitude even though the 10 m s\(^{-1}\) threshold wind speed was exceeded for more than 6 hours. Maximum wind speeds on 15 June were near 16 m s\(^{-1}\) and produced PM\(_{10}\) concentrations of 4.68 mg m\(^{-3}\). Winds of up to 11 m s\(^{-1}\) on 16 June produced a maximum PM\(_{10}\) concentration of less than 1 mg m\(^{-3}\) at the 2-m height. The maximum PM\(_{10}\) vertical flux for this event was 0.095 mg m\(^{-2}\) s\(^{-1}\). Horizontal sediment flux during this event was 0.06 kg m\(^{-1}\) min\(^{-1}\) over the PM\(_{10}\) emission period in the 36-day BSNE sampling interval.

4. Discussion

The measured horizontal sediment fluxes during the early September 2010 wind event were more than four orders of magnitude larger than values reported by Sankey et al. (2009) for natural conditions in this area (Table 2). Although PM\(_{10}\) data were not available between 1-30
August 2010, based on observed wind speeds and horizontal sediment fluxes, we suspect that PM$_{10}$ concentrations were elevated on a nearly daily basis, with spikes in concentration on a few particularly windy days such as 17 August (Fig. 5). Despite these suspected earlier emissions, based on the high sustained wind speeds and relative peak in horizontal sediment flux, we believe the largest PM$_{10}$ emissions occurred during the early September 2010 event, making this event the largest in terms of both horizontal sediment flux and PM$_{10}$ vertical flux. The MODIS satellite imagery clearly depicts the burned area as the source of dust emissions during this wind event and provides visual evidence of the areal extent of the dust emissions. The cumulative horizontal sediment flux during this episode is similar in magnitude to that reported during major wind erosion events on agricultural fields in the U.S. (Fryrear, 1995; Table 2) and the Loess Plateau in China (Dong et al., 2010; Table 2).
Table 2. Horizontal sediment fluxes measured in this study compared to values reported in the literature.

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Sediment Trap</th>
<th>Duration (days)</th>
<th>Horizontal Sediment Flux (kg m(^{-1}))</th>
<th>Measurement Height (m)</th>
<th>Integration Height(^c) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study(^a)</td>
<td>Post-fire, Idaho</td>
<td>BSNE</td>
<td>13</td>
<td>1495</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>This study(^a)</td>
<td>Post-fire, Idaho</td>
<td>BSNE</td>
<td>14</td>
<td>120</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Dong et al. (2010)</td>
<td>Loess Plateau, China</td>
<td>LDD</td>
<td>30</td>
<td>800</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Fryrear (1995)</td>
<td>Elkhart, Kansas</td>
<td>BSNE</td>
<td>1</td>
<td>1236</td>
<td>2</td>
<td>TSS height</td>
</tr>
<tr>
<td>Fryrear (1995)</td>
<td>Big Spring, Texas</td>
<td>BSNE</td>
<td>1</td>
<td>351</td>
<td>2</td>
<td>TSS height</td>
</tr>
<tr>
<td>Fryrear (1995)</td>
<td>Crown Point, Indiana</td>
<td>BSNE</td>
<td>1</td>
<td>344</td>
<td>2</td>
<td>TSS height</td>
</tr>
<tr>
<td>Fryrear (1995)</td>
<td>Eads, Colorado</td>
<td>BSNE</td>
<td>1</td>
<td>479</td>
<td>2</td>
<td>TSS height</td>
</tr>
<tr>
<td>Fryrear (1995)</td>
<td>Sidney, Nebraska</td>
<td>BSNE</td>
<td>1</td>
<td>249</td>
<td>2</td>
<td>TSS height</td>
</tr>
<tr>
<td>Leys and McTainsh (1996)</td>
<td>Australia</td>
<td>BSNE</td>
<td>7</td>
<td>213</td>
<td>2</td>
<td>2.3</td>
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<tr>
<td>Nickling (1978)</td>
<td>Yukon</td>
<td>MB</td>
<td>&lt;1</td>
<td>186</td>
<td>12</td>
<td>12</td>
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<tr>
<td>Pease et al. (2002)</td>
<td>North Carolina</td>
<td>MWAC</td>
<td>-</td>
<td>126</td>
<td>2.2</td>
<td>TSS height</td>
</tr>
<tr>
<td>Riksen and Goosens (2005)</td>
<td>Netherlands</td>
<td>MWAC</td>
<td>7</td>
<td>2000</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Sankey et al. (2009)</td>
<td>Post-fire, Idaho</td>
<td>BSNE</td>
<td>30</td>
<td>5.4</td>
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<td>2</td>
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<td>Sankey et al. (2009)</td>
<td>Unburned, Idaho</td>
<td>BSNE</td>
<td>30</td>
<td>0.08</td>
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<tr>
<td>Sharratt and Feng (2009)</td>
<td>Columbia Plateau</td>
<td>BSNE</td>
<td>&lt;1</td>
<td>1.9</td>
<td>1.5</td>
<td>5</td>
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<td>Sharratt et al. (2007)</td>
<td>Columbia Plateau</td>
<td>BSNE</td>
<td>3</td>
<td>22</td>
<td>1.5</td>
<td>5</td>
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<tr>
<td>vanDonk et al. (2003)</td>
<td>Mojave Desert</td>
<td>BSNE</td>
<td>30</td>
<td>77</td>
<td>1</td>
<td>2</td>
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<tr>
<td>Van Pelt et al. (2004)</td>
<td>Big Spring, Texas</td>
<td>BSNE</td>
<td>1</td>
<td>626</td>
<td>1</td>
<td>TSS height</td>
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</tbody>
</table>

\(^a\) Maximum and minimum horizontal sediment fluxes measured during this study.

\(^b\) BSNE = Big Spring Number Eight; LDD is a modified BSNE; MB = Modified Bagnold trap; MWAC = Modified Wilson and Cooke.

\(^c\) TSS = Transition height between saltation and suspension; described in Fryrear and Saleh (1993).
Table 3. PM$_{10}$ ambient concentrations and vertical fluxes measured in this study compared to values reported in the literature.

<table>
<thead>
<tr>
<th>Study</th>
<th>Sensor/Method</th>
<th>Date</th>
<th>Duration (hr)</th>
<th>Max Concentration (µg m$^{-3}$)</th>
<th>$F_{v}$ (µg m$^{-2}$ s$^{-1}$)</th>
<th>Averaging Period, Measurement Height$^{a}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td>E-Sampler</td>
<td>4 Sep 2010</td>
<td>7.5</td>
<td>69000</td>
<td>3030</td>
<td>5 min, 2 m</td>
</tr>
<tr>
<td>This study</td>
<td>E-Sampler</td>
<td>5 Sep 2010</td>
<td>11</td>
<td>37100</td>
<td>3230</td>
<td>5 min, 2 m</td>
</tr>
<tr>
<td>This study</td>
<td>E-Sampler</td>
<td>3 Oct 2010</td>
<td>1</td>
<td>40200</td>
<td>1500</td>
<td>5 min, 2 m</td>
</tr>
<tr>
<td>This study</td>
<td>E-Sampler</td>
<td>4 Oct 2010</td>
<td>2</td>
<td>6480</td>
<td>2760</td>
<td>5 min, 2 m</td>
</tr>
<tr>
<td>This study</td>
<td>E-Sampler</td>
<td>4 Oct 2010</td>
<td>1.5</td>
<td>14970</td>
<td>2630</td>
<td>5 min, 2 m</td>
</tr>
<tr>
<td>This study</td>
<td>E-Sampler</td>
<td>28 Apr 2011</td>
<td>5</td>
<td>48500</td>
<td>3680</td>
<td>5 min, 2 m</td>
</tr>
<tr>
<td>This study</td>
<td>E-Sampler</td>
<td>28 Apr 2011</td>
<td>3</td>
<td>35700</td>
<td>1490</td>
<td>5 min, 2 m</td>
</tr>
<tr>
<td>This study</td>
<td>E-Sampler</td>
<td>15 Jun 2011</td>
<td>7</td>
<td>4680</td>
<td>94.8</td>
<td>5 min, 2 m</td>
</tr>
<tr>
<td>Gillette et al. (1997)</td>
<td>Portable filter</td>
<td>11 Mar 1993</td>
<td>1.5</td>
<td>-</td>
<td>-</td>
<td>235</td>
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<tr>
<td>Kjelgaard et al. (2004)</td>
<td>TEOM, Hi-vol</td>
<td>1 Sep 2002</td>
<td>13</td>
<td>6000</td>
<td>25</td>
<td>10 min, 3 m</td>
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<tr>
<td>Sharratt and Feng (2009)</td>
<td>E-Sampler, Hi-vol</td>
<td>29-30 Aug 2006</td>
<td>16</td>
<td>2580</td>
<td>81</td>
<td>5 min, 3 m</td>
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<td>Sharratt et al. (2007)</td>
<td>TEOM, Hi-vol</td>
<td>27-29 Oct 2003</td>
<td>14</td>
<td>8535</td>
<td>255</td>
<td>10 min, 5 m</td>
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<tr>
<td>Thorsteinsson et al.</td>
<td>Back-trajectory</td>
<td>2008</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9720</td>
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<td>model</td>
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<td>Stout et al. (2001)</td>
<td>Minivol</td>
<td>13 Apr 1996</td>
<td>24</td>
<td>-</td>
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<td>- 2 m</td>
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<td>Zobeck and VanPelt (2006)</td>
<td>DustTrak</td>
<td>18 Mar 2003</td>
<td>2.5</td>
<td>2000</td>
<td>400</td>
<td>1 min, 2 m</td>
</tr>
</tbody>
</table>

$F_{v}$ is PM$_{10}$ vertical flux.

$^{a}$Averaging period is the period over which the time-resolved PM$_{10}$ concentrations were averaged; this value is not reported for sensors which do not provide time-resolved PM$_{10}$ concentrations. Measurement height is the height at which the reported concentration measurements were made.
Horizontal sediment fluxes and PM$_{10}$ vertical fluxes were smaller after the early September 2010 event, likely due to decreased availability of erodible surface material; however, there was substantial horizontal sediment flux in early November 2010 prior to snowfall. This indicates there was still sufficient erodible soil available to produce dust emissions. While PM$_{10}$ emissions and horizontal sediment fluxes were smaller during mid-September 2010 to November 2010 as compared to the July 2010 to early September 2010 period, PM$_{10}$ emissions were still in the mid to high range of values reported for agricultural soils (Fryrear, 1995; Sharratt et al., 2007; Van Pelt et al., 2004; Table 2). Peak PM$_{10}$ concentrations measured during the September 2010 event were two orders of magnitude larger than PM$_{10}$ concentrations reported from high wind events on the Columbia Plateau in central Washington (Sharratt et al., 2007; Table 3) and three orders of magnitude larger than those reported during high wind events on the US southern high plains (Stout, 2001; Table 3). PM$_{10}$ vertical fluxes during fall 2010 were an order of magnitude larger than values reported for agricultural soils in the U.S (Sharratt et al., 2007) and on the order of the value reported by Thorsteinsson et al. (2011) for sand plains in Iceland (Table 3). PM$_{10}$ vertical fluxes during spring 2011 were smaller than during fall 2010 but were still on the upper end of values reported for agricultural soils in the U.S. (Sharratt et al., 2007; Sharratt and Feng, 2009; Zobeck and Van Pelt, 2006; Table 3). Ratios of PM$_{10}$ vertical flux to horizontal sediment flux ranged from the upper end of to ten times those reported by Gillette et al. (1997; range of 0.00005–0.05 m$^{-1}$) for sand, loamy sand, clay, and loam soils at a dry lake bed and up to 100 times those reported by Sharratt and Feng (2009; range of 0.001–0.003 m$^{-1}$) for disturbed agricultural soils on the Columbia Plateau (Table 1).
Although smaller than the earlier September 2010 event, the October event constituted a major wind erosion episode with horizontal sediment fluxes on the same order of magnitude as those reported from large wind erosion events measured from other types of disturbed soils (Sharratt et al., 2007; van Donk et al., 2003; Table 2) and PM$_{10}$ vertical fluxes larger than those reported from agricultural soils (Zobeck and Van Pelt, 2006; Table 3).

The horizontal sediment flux and PM$_{10}$ measurements made in early April 2011 were on the same order of magnitude as those measured during October 2010. Wind erosion activity in spring 2011 prompted land managers to install straw bales along a county road downwind of the fire to trap wind-blown sediment and protect the roadway (Fig. 9). By June 2011, however, vegetation began to reestablish on site and helped to stabilize the surface soils. There was a decrease in horizontal sediment flux and PM$_{10}$ vertical flux after the vegetation started to recover. Total ground cover was still relatively low (17%) at the end of our field campaign in July, but apparently sufficient to protect surface soils enough to attenuate sediment transport and PM$_{10}$ vertical flux by about 33% and 93%, respectively, when the June 2011 measurements are compared to those during April 2011 (Table 1).
Vegetation recovery was facilitated by adequate spring rainfall at the site (48% of the average annual precipitation between April and July). It is possible that if the spring months had been drier than usual, the vegetation may not have recovered as quickly and dust emissions would have persisted for a longer period of time. This has been the case for other post-fire sites, such as the areas burned by the Milford Flat Complex in Utah and the Cerro Grande Fire in New Mexico, where persistent post-fire drought conditions inhibited vegetation regrowth and produced elevated dust emissions for years after the fires (Miller et al., 2010; Whicker et al., 2006). This is not an unlikely scenario as wildfires frequently occur in periods of drought that often continue into the next season and make vegetation recovery difficult and leave the soil more susceptible to erosion.

5. Conclusions
On-site horizontal sediment flux and PM$_{10}$ concentration measurements provided a quantitative account of wind erosion in the area burned by the 2010 Jefferson Fire. We determined threshold wind speeds and corresponding threshold friction velocities to be 6.0 and 0.20 m s$^{-1}$, respectively for the fall 2010 period and 10 and 0.55 m s$^{-1}$ for the spring 2011 period. Five percent of the horizontal sediment transport was PM$_{10}$ and 60% of the PM$_{10}$ fraction was PM$_{2.5}$ during the four months following the fire. We measured a maximum PM$_{10}$ vertical flux of 32.3 mg m$^{-2}$ s$^{-1}$ and maximum total horizontal sediment flux of 0.34 kg m$^{-1}$ min$^{-1}$. To our knowledge, this is the first study to report on-site measurements of PM$_{10}$ vertical flux from a post-fire environment in tandem with measurements of horizontal sediment flux. Horizontal sediment fluxes were sufficiently large to obscure the PM$_{10}$ concentration gradient between 2 and 5 m above the soil surface, prohibiting calculation of PM$_{10}$ vertical flux based on gradient transport theory within this region. To mitigate this issue, a Gaussian profile was used to estimate PM$_{10}$ concentrations at a height of 10 m and the concentration gradient between 5 and 10 m was used to calculate PM$_{10}$ vertical flux. This suggests that application of the gradient transport theory for calculating PM$_{10}$ vertical flux should be limited to regions above the zone of horizontal transport. The extremely high PM$_{10}$ concentrations measured in this study, in some cases, exceeded the limits of the PM$_{10}$ sensors. The need to accurately measure on-site particle concentrations in order to quantify particle emission rates from major dust sources requires improvements to existing instrumentation or development of new measurement techniques that are more capable of handling these large particle concentrations.

These results indicate that wildfire can convert a relatively stable landscape into a highly erodible source of particulate emissions and that horizontal sediment flux and PM$_{10}$ emissions can remain elevated for months following a fire. Burned soils can produce large horizontal
sediment fluxes, comparable to those of the most wind erodible landscapes in the US, as well as high vertical fluxes of PM$_{10}$, with estimated values near the upper end of values reported from other types of soil disturbance.

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References


CHAPTER FIVE
SUMMARY AND FUTURE WORK

The focus of this dissertation was to evaluate and develop a high resolution wind model, WindNinja, for wildfire-related applications in complex terrain. Chapter 2 described high-resolution observational datasets of near-surface winds collected from two types of complex terrain features. Unique flow features for each terrain feature were presented and investigated. These datasets constitute a significant contribution to the archive of observational data available for evaluating wind predictions in complex terrain. The datasets have been made publicly available via a web-based portal. Chapter 3 described use of the observational datasets to evaluate near-surface wind predictions from a suite of Numerical Weather Prediction (NWP) models as well as the effect of dynamically downscaling those predictions with the WindNinja model. Results demonstrated that, at least in areas of moderately complex terrain where the average approach flow to the area of interest can be adequately defined (e.g., the isolated mountain in this study), NWP near-surface wind predictions can be improved via dynamical downscaling with WindNinja. In other words, the benefits of downscaling surface wind predictions are limited by the quality of the initial wind field. Areas with more extensive complex terrain (e.g., the Salmon River Canyon site in this study) require higher resolution NWP runs to capture important flow features induced by the surrounding terrain as input to the WindNinja model. These findings have important implications for modeling surface-wind sensitive processes, such as wildland fire behavior and wind erosion, in areas with complex terrain. Chapter 4 described some of the first measurements of wind erosion from a landscape burned by wildfire. Results demonstrated that post-fire landscapes can be significant sources of
PM$_{10}$ and that dust emissions can persist for up to a year post-fire. Data collected during this study will be useful for evaluations of PM$_{10}$ emission algorithms applied to burned landscapes.

The work presented in this dissertation has led to ideas for future research efforts and further development of the WindNinja modeling framework. Results from the model evaluations study (Chapter 3) suggested a potential problem in the parameterization of the diurnal slope flow model used in WindNinja, particularly at the Salmon River Canyon site where upslope/downslope wind speeds were consistently over-predicted. Future work should re-evaluate this parameterization using selected upslope/downslope test cases from the high resolution wind dataset described in Chapter 2. Specifically, the drag coefficients employed by the slope flow model should be further tested. One of the unique features of the WindNinja modeling approach is the fast run times associated with the mass-consistent solution technique that it uses. There is a loss in accuracy associated with this approach; however, in many cases the, the loss in accuracy that arises from not including more complete physics in the flow solution is offset by the fast runs times. An optional momentum solver is being developed that will soon be implemented as an optional feature within the WindNinja framework. Use of the momentum solver will likely improve predictions in areas of enhanced turbulence, such as the lee side of terrain features, but will result in slow run times. The decision to enable/disable this feature will ultimately be up to the user and will depend on their specific application and time constraints. The WindNinja framework is being extended to also include an optional PM$_{10}$ emissions algorithm for post-fire areas as well as a scalar transport equation which will allow for simulation of transport and diffusion of PM$_{10}$.