ABSTRACT: Spatial variability in the seasonal snowpack is affected by many factors, but wind redistribution, in addition to snowfall rate and sublimation, are the most complex and therefore the least understood. Modeling how wind affects snow redistribution in heterogeneous terrain from first principles is computationally intensive and requires knowledge of the forcings at a resolution that is typically not available. Complex physics-based models have been developed to predict where drift and scour zones develop using meteorological and topographical data. Operational use of such models at scales needed for water resource planning and avalanche forecasting is not currently practical. A simplified, computationally intensive wind model which requires a minimum of typically available forcings has been developed that searches for terrain breaks in upwind directions, and has been found to accurately predict drift zones. We will validate this model using high-resolution snow depth data derived from airborne LiDAR, with the eventual goal of evaluating the effects of vegetation on wind redistribution. High resolution DEMs were developed from LiDAR surveys for two study sites in the western United States, each chosen for their unique climate and topography as well as their availability of data. The first site exhibits a high-desert/alpine climate with a slightly wind-affected snowpack, and the second a complex, avalanche-prone section of an Idaho highway corridor in which we will model the potential for wind loading of snow in starting zones. Preliminary results, which have been supported with ground truth measurements at the first site, are very encouraging for a wider implementation.

1. INTRODUCTION

In the study of seasonal snow, there are many factors affecting spatial variation in snow depths at the hillslope scale, including short and longwave radiation, vegetation density, and topography. But the largest cause of variability in complex terrain has been shown to be prevailing winds during storm events (Elder et al. 1991; Luce et al. 1998; Seyfried and Wilcox 1995). These strong wind events scour snow from windward locations and preferentially deposit the airborne snow in drifts on the leeward sides of topographical features.

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Modeling wind redistribution from a digital elevation model (DEM) provides field researchers and practitioners with helpful a priori knowledge of estimated snow distributions. Consequently, numerous modeling techniques have been developed to accurately predict locations of drift and scour zones. These models range in complexity from largely physics-based (Lehning et al. 2006; Liston and Sturm 1998) to simple slope finding algorithms (Winstral et al. 2002). Though the complexity and computational efficiency of these models vary significantly, the cell size of input DEM terrain information have typically been on the order of 10 meters. Topography and vegetation distribution, and therefore wind fields, can change drastically in alpine basins at length scales much less than 10 meters. The goal of this research is to apply the Winstral et al. [2009] wind redistribution model to a higher resolution DEM which includes vegetation height information in complex mountainous terrain.
Historically, 10-30 meter DEMs have been produced from geological survey topographical data. Airborne Light Detection And Ranging (LiDAR) is a relatively new technology that allows researchers to create higher resolution (<1m to 5m) DEMs that were previously unavailable. For an airborne LiDAR survey, the sensor is flown aboard a small aircraft and measurements are corrected with onboard GPS and an Inertial Measurement Unit (IMU). Vertical and horizontal accuracy is typically about 10-50 cm and 5-20 cm, respectively (Liu 2011). At this resolution, topographical nuances are visible that can be absent at a coarser resolution. An added benefit of this resolution is the ability to include vegetation heights, in addition to a bare earth product, as a model input. This will aid in predicting wind fields not only from topography but also from vegetation cover, which could be an important component of mountain snow distribution. In addition to detailed topography, repeat LiDAR surveys during the winter months can be used to estimate snow depth.

The wind redistribution model described in Winstral et al. 2002 defines terrain parameters that label individual cells as either scour or drift zones. The model was developed at the Reynolds Creek Experimental Watershed in Southwestern Idaho (Fig. 1), in terrain that accumulates massive drifts over 3 meters deep with surrounding snow depths of approximately 1 meter. The wind model, when paired with the ISNOBAL energy-balance model (Marks et al. 1999), substantially improved the prediction of the spring melt-out (Marks et al. 2002). We use high-resolution DEMs as input to this wind model for two study sites in central Idaho. Each site was chosen first and foremost by the availability of LiDAR survey data, which is currently very expensive to obtain and not widely available.

This work will qualitatively study the correlations between the model output terrain parameters and snow depths as estimated by repeat LiDAR surveys. Future work will study this correlation more quantitatively with the hopes of predicting snow depths from snow-free topography data.

2. STUDY SITES

2.1 Dry Creek Experimental Watershed

Located approximately 16 km northeast of Boise, Idaho (Fig. 1), the Dry Creek Experimental Watershed (DCEW) is a 28 km² intensive hydrological study site rising from 1000-2100 meters above sea level. Two airborne LiDAR surveys were conducted in November, 2007 and March, 2009 to measure a ‘snow-free’ and ‘snow-on’ surface, respectively. When differenced from the ‘snow-free’ surface, the ‘snow-on’ surface provides a high resolution snapshot of snow depths at an instant during the winter. The point density of this particular LiDAR survey yielded 1-meter resolution DEM and snow depth products over the entire watershed. A ground-truth campaign was conducted during each of the LiDAR flights.

The topography of this site is characterized by high-desert foothills in the lower drainage and mountainous, subalpine forests in the upper drainage. This study will focus on wind...
redistribution of snow in a 0.77 km\(^2\) portion of the upper basin.

### 2.2 Canyon Creek Peak, Banner Summit

Along Highway 21 between Lowman and Stanley, Idaho is a stretch of road with a high-degree of avalanche danger and is the only section of highway in Idaho that is actively controlled. Idaho Transportation Department forecasters observe and predict avalanche danger throughout the winter season using weather information, manual measurements and a degree of intuition based on many valuable years of experience to determine when to close and re-open the highway corridor during a storm cycle. Over two days in the middle of January, 2012 thirty-seven separate slides reached the highway along a six-mile stretch of the canyon. Our research group has active projects monitoring avalanches with infrasound and modeling snow slope stability.

In August, 2011 an airborne LiDAR survey was conducted over the main starting zones on the western side of the highway along Canyon Creek Peak. Due to the steep terrain and point density, a lower resolution 2-meter DEM was created to eliminate data holes in the terrain surface. The wind model was then applied to predict deposition zones in avalanche terrain to hopefully aid in forecasting the possible wind-loading of leeward slopes during storms. This wind redistribution model has not previously been applied to such complex and avalanche-prone terrain.

### 3. TERRAIN MODELING

As previously mentioned, wind fields in mountainous terrain are extremely complex. The method developed by Winstral et al. [2002] remains a viable model for describing wind flow separation using a gridded DEM. Recently, researchers with the WSL Institute for Snow and Avalanche Research concluded that the output terrain parameters from this wind redistribution model are significantly comparable to snow depth measurements from terrestrial LiDAR surveys (Schirmer et al. 2011).

The model determines the maximum upwind slope, \( S_x \), over a user-defined search vector, \( d_{\text{max}} \), from each grid cell (Winstral et al. 2009).

\[
S_{x,d_{\text{max}}} = \max\left(\tan^{-1}\left(\frac{\text{elevation difference}}{\text{distance between cells}}\right)\right)
\]

The slope value is then assigned to the same cell position in a new grid. This parameter describes the relative exposure of a cell for a given upwind direction.

Next, the model calculates the difference, \( S_b \), between a new calculated parameter, \( S_{x,\text{local}} \), and the upwind slope, \( S_{x,\text{local}} \), found by searching the maximum upwind slope along a vector \( \text{sepdist} = 100 \) meters. Next, \( S_{x,\text{outlying}} \) is found by searching from the end of \( \text{sepdist} \) along a search vector \( d_{\text{max}} = 1000 \) meters. A \( S_b \) value > 5° is normally considered to be a drifting zone.

**Fig. 2** – This sample elevation profile illustrates the calculation of maximum upwind slope as well as features that create wind flow separation. \( S_{x,\text{local}} \) is found by searching for the maximum upwind slope along a vector \( \text{sepdist} = 100 \) meters. Next, \( S_{x,\text{outlying}} \) is found by searching from the end of \( \text{sepdist} \) along a search vector \( d_{\text{max}} = 1000 \) meters. A \( S_b \) value > 5° is normally considered to be a drifting zone.
defined by a search vector, sepdist, and $S_{x,\text{outlying}}$ defined by $d_{\text{max}}$ (sepdist < $d_{\text{max}}$). This parameter determines if any topographical features exist upwind that may separate wind flow, and consequently allow drift formation over the cell of interest.

$$S_b = S_{x,\text{local}} - S_{x,\text{outlying}}$$  \hspace{1cm} (2)

These values are calculated for a range of upwind directions, and then averaged over a 30° window to provide a measure of terrain parameters that are less sensitive to small changes in wind direction. **Fig. 2** depicts a sample elevation profile of a 20-meter DEM with the cell of interest existing in a drift-formation zone.

4. RESULTS

4.1 **Dry Creek**

The Upper Dry Creek site was the first site to be evaluated with the wind redistribution model using a 1-meter DEM. From weather station data gathered over multiple seasons, the resultant mean upwind direction during storm events was found to exhibit a bimodal distribution (**Fig. 3**). Due to the lack of one true mean wind direction, we can see that to properly predict snow depth over an entire season, the model must be applied on a storm to storm basis using individual storm resultant wind directions.

At 1-meter DEM resolution, the $S_b$ parameter

![Fig. 2 - Sample elevation profile of a 20-meter DEM with the cell of interest existing in a drift-formation zone.](image)

![Fig. 3 - Upper Dry Creek wind rose for the 2007/2008 winter season. Only wind events capable of transporting snow [5-15 m/s] (Li and Pomeroy 1997) and an air temperature < 2° C are depicted.](image)

![Fig. 4 - Dry Creek qualitative comparison between 1-m resolution snow depths (a) measured in March, 2009 and a calculated wind flow separation parameter, $S_b$ (b), calculated from the snow-free DEM over the 880 m² study site. The model input was a wind direction of 210°, $d_{\text{max}} = 700$ meters and sepdist = 70 meters.](image)
calculated from a bare earth, snow-free surface displays a promising qualitative correlation with snow depth using an upwind direction of 210°, a \(d_{\text{max}}\) value of 700m, and a \(\text{sepdist}\) value of 70m (Fig. 4). One factor that has not yet been considered is the effect of solar radiation, which is known to be a major driver of the Dry Creek snow distribution. Further study will investigate the coupled effects of wind distribution and incoming shortwave radiation on snow depth in this watershed, and will involve combining the wind model with a snow energy balance model to evaluate both drivers of variability.

4.2 Banner Summit

Very few ground-based measurements have been made within the avalanche starting zones due to the inherent risk involved. Furthermore, as of yet no LiDAR surveys have been carried out during the winter months. Therefore, we can only use the snow-free surface as model input to show approximate locations of wind-loading. This is a first attempt to evaluate the usefulness of a simple wind redistribution model as a tool for avalanche forecasting.

Fig. 5 shows the resulting image of the \(S_b\) parameter as a textural overlay on the terrain surface. This calculation used a wind direction of 270°, \(d_{\text{max}} = 1000m\), \(\text{sepdist} = 100m\) and, as mentioned before, a 2-meter resolution DEM.

A consideration that must be made is that the downwind extent of modeled ridge line drifting is completely dependent upon the value of \(\text{sepdist}\). This is because the ridge is the highest terrain feature in the vicinity, and therefore the model predicts large slope breaks for all points within \(\text{sepdist}\) of the ridge. Under normal circumstances, \(\text{sepdist}\) can be measured in the field by taking depth measurements along transects to approximate drifts’ lateral extents. In the coming winter a campaign will be conducted to characterize the widths of starting zone drifts atop Canyon Creek Peak.

Fig. 5 – Wind flow separation parameter, \(S_b\), across the summit avalanche starting zones of Canyon Creek Peak. Upwind direction is due west (270°) and the search vectors are \(d_{\text{max}} = 1000\) meters and \(\text{sepdist} = 100\) meters.
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6. REFERENCES


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