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Merging a terrain-based parameter with blowing snow fluxes for assessing snow redistribution in alpine terrain

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ABSTRACT

Wind and the associated snow transport are dominating factors determining the snow distribution and accumulation in alpine areas. These factors result in a high spatial variability of snow heights that is difficult to quantify. In this study, we propose an efficient method for estimations of changes in snow heights during blowing snow events. We merge a terrain-based parameter Sx, which characterizes the degree of shelter or exposure of a point provided by the upwind terrain, with estimations of quantity of snow transported by the wind. This estimation is provided by snow particle counters (SPC) that estimate the snow flux, the mass of drifting snow particles per time and area. A modified terrain-based parameter Sx_m is then used to distribute snow over the terrain. The results are compared with measured changes in snow heights resulting from blowing snow events, obtained with terrestrial laser scanning (TLS). Data and results are from the Col du Lac Blanc research site in the French Alps. We use a high raster resolution of 1 m, which is required when assessing the snow-redistribution situation in highly structured terrain or in the starting zones of small and medium-sized avalanches. Results show that the proposed method can estimate snow distributions based on a modified terrain parameter Sx_m and measured snow flux data. It can reproduce patterns of snow redistribution and estimate changes in snow heights reasonably well, as shown by correlation coefficients (R) of 0.78 to 0.86. The derivation of the modified terrain parameter Sx_m and snow flux are specific to the research site and not yet generally applicable. The formulations require the calibration and alteration of two parameters only for use in studies with other terrain and weather characteristics.

1. Introduction

Wind and associated snow transport are the dominating factors determining small-scale snow distribution and accumulation in alpine areas, resulting in a substantial spatial variability in snow heights. Describing snow redistribution due to wind both qualitatively and quantitatively is of great interest for snow and avalanche professionals and researchers. Several numerical models were developed in the last decades to simulate blowing and drifting snow. More recent examples include Meso-NH/Crocus (Vionnet et al., 2014), SnowDrift3D (Schneiderbauer and Prokop, 2011), Alpine 3D (Lehning et al., 2008), and SYTRON3 (Durand et al., 2005).

An alternative to these complex numerical models has been proposed by Winstral and Marks (2002). They developed a cost-effective algorithm to predict snow distribution based on the terrain-based parameter Sx. The parameter quantifies the degree of shelter or exposure of a point provided by the upwind terrain. The work of Winstral et al. (2002) shows that Sx is a significant predictor of snow water equivalent (SWE) and has a stronger relationship to observed variances in SWE than the variables elevation, potential net solar radiation and slope. Winstral and Marks (2002), Erickson et al. (2005), Molotch et al. (2005), Schirmer et al. (2011) and Winstral et al. (2013) report similar observations of the effect and significance of Sx on the distribution of snow. These studies covered entire alpine basins or catchments for the purpose of hydrological modeling (in the range of 0.1 to several km^2) and used raster resolutions of 10–30 m.

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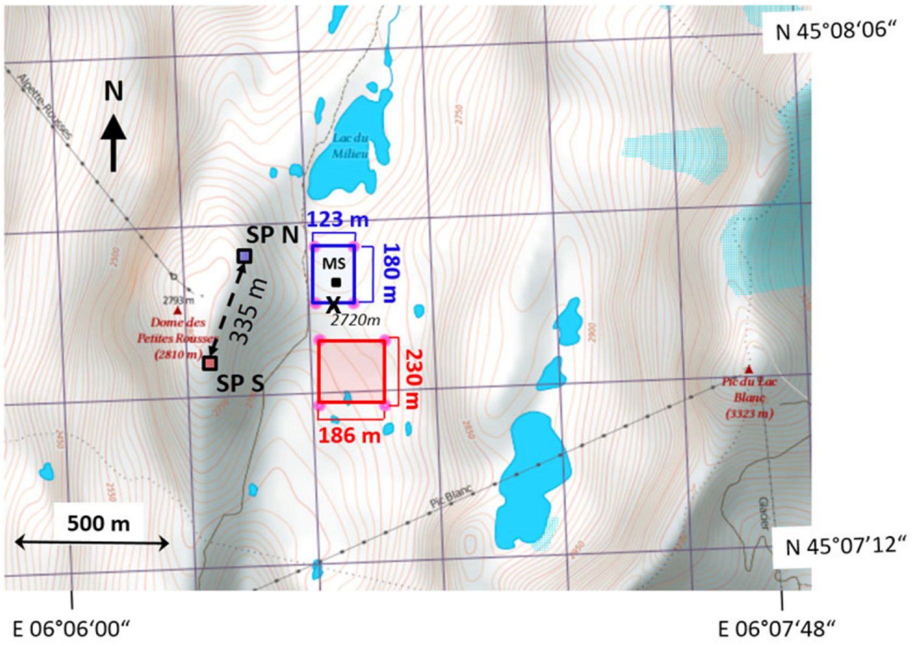

Fig. 1. Map of the study site with the areas of the case studies case study I (north, blue frame) and case study II (south, red frame). MS = meteorological station; X = pass and location of the SPC; also shown are the two scan positions (SP N = scan position north, SP S = scan position south), approximately 335 m apart; lat/long grid for reference; contour lines = 10 m. Source: FranceTopo.fr (2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Sx is not defined as or derived from a physical model, however. It describes solely the terrain component and its influences controlling snow redistribution. Therefore, it does not provide a quantitative estimate of changes in snow heights. Sx has been used, however, to modify wind fields and precipitation and as additional input into mass and energy balance models. Winstral and Marks (2002) and Winstral et al. (2013) used the parameter Sx to simulate wind fields and snow redistributions for input to Isnobal, a distributed two-layer mass- and energy-balance snowmelt model (Marks et al., 1999). The authors accounted for zones of flow separation and resulting enhanced snow redeposition with accumulation factors. The simulated snow-water-equivalent distributions forced with the developed algorithm are far more accurate than simulations without a wind-affected accumulation component. Winstral et al. (2002), Winstral and Marks (2002), and Winstral et al. (2013) delineated topographic features capable of generating flow separation and enhanced snow accumulations on the leeside with a parameter Sb. Sb uses two applications of Sx to determine a local and an outlying Sx.

Schirmer et al. (2011) used Sx to distribute wind and precipitation fields for input to Alpine3D (Lehning et al., 2006). The authors show that Sx can qualitatively reproduce the patterns of snow distribution at the time of the maximum snow height. Sx fails, however, to reproduce the magnitude of the observed variability, and, when applied in Alpine3D, cannot reconstruct the total snow height distributions.

The terrain-based parameter Sx has shown to qualitatively predict snow redistribution with good reproduction of spatial patterns. Raster resolutions of 30–100 m are sufficient for hydrological assessments of snow redistribution and melt on watershed scale (Winstral et al., 2013). Analyzing avalanche starting zones requires higher resolutions. The presentation of terrain features that favour snow accumulation in avalanche release areas requires digital terrain or snow surface models with a raster resolution of < 10 m. Snow heights and the related instabilities can change substantially within the distance of one or two meters. Furthermore, small-scale terrain features where both terrain and snow cover are changing rapidly are associated with avalanche triggering, particularly near ridge crests (McClung and Schaerer, 2006).

Veitinger et al. (2015) note that coarse-scale elevation models (> 10 m) are limited to delineating start zones of extreme avalanche scenarios with very high return periods. Higher resolutions that can capture surface roughness are highly relevant for smaller, more frequent avalanches. Such avalanches cause the majority of casualties in Switzerland, and also put mountain transport ways and ski runs at risk (Maggioni et al., 2012; Veitinger et al., 2015). Consequently, there is a need for a method that can represent the redistribution of snow by wind in high spatial resolution.

In a previous study from the Col du Lac Blanc test site in the French Alps, Schön et al. (2015) applied Sx to reproduce snow redistribution patterns, using 1 m raster resolutions. Results are from two approximately 10 m high terrain edges. Estimated changes in snow heights were compared with measured changes in snow heights, obtained with terrestrial laser scanning (TLS). Schön et al. (2015) demonstrate how correlations of Sx with measured changes in snow heights improve when a digital snow surface model is used, as opposed to a digital elevation model. Then estimated changes in snow height (ΔHS_{est}) due to redistribution by wind can be calculated with $\Delta HS_{est} = \alpha * Sx$. The value of the parameter α showed to be linked to the observation times and amount of snow deposited. However, the linear relationship between Sx and α did not properly account for the increased snow accumulation on lee areas with flow separation, and the authors could not determine a proxy for the parameter α.

We present an additional method, based on two different tools: i) a terrain-based parameter Sx_m, modified to better capture regions of enhanced snow accumulation; Sx_m characterizes the degree of shelter or exposure of a grid point provided by the upwind terrain, and ii) snow flux data from snow particle counters (SPC), as proxy for transported snow and proxy the value of the parameter α. Thus, the SPC provide data about the duration and intensity of drifting snow events, two important factors not accounted for by the terrain parameter Sx.

Our approach differs from the studies cited above, where a terrain-based parameter is combined with precipitation data. Instead of using precipitation, we use estimates of snow mass transported by wind. This approach can be beneficial in high-altitude areas like the Col du Lac Blanc, where in winter snow transport without concurrent falling snow can occur up to 60% of the time (Vionnet et al., 2013).

2. Data and methods

2.1. Case studies

Our results are from the Col du Lac Blanc in the French Alps (Fig. 1). The pass is located at 2720 m a.s.l. and well-suited for our research due to consistently bi-modal wind directions (north-east or south), the