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A Comparison of Terrain-Based Parameter, Wind-Field Modelling and TLS Snow Depth Data for Snow Drift Modelling

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ABSTRACT: Wind and the associated snow drift are dominating factors determining the snow distribution and accumulation in alpine areas, resulting in a in high spatial variability of snow depth that is difficult to evaluate and quantify. In our study, we compare the results of a terrain-based parameter to snow-depth distribution and redistribution data obtained by high-accuracy TLS (Terrestrial Laser Scan) and to the results of wind-field simulations. Our results are from the test site at the Col du Lac Blanc, close to the ski resort of Alpe d'Huez in the French Alps, an area particularly suited for our study due to its constant wind direction, the availability of wind and precipitation data from a meteorological station and data from multiple TLS scan campaigns. We first spatially identify areas of good and poor correlation between terrain-based parameter and measured data, and identify common characteristics for these areas. Second, we present the differences in the results of the terrain-parameter based on a) summer terrain and b) snow-covered surface in mid-winter, and show how this affects the spatial correlation with the measured snow depth data. Third, we present comparisons of the terrain-based parameter to wind-field simulations with ARPS (Advanced Regional Prediction System), a 3-dimensional atmospheric model for simulating microscale airflows. The results of our study are another step towards improving the terrain-based parameter's ability to quantitatively describe snow redistribution.

KEYWORDS: snow, wind, redistribution, TLS, terrain parameter, ARPS

1 INTRODUCTION

In alpine areas, wind and snow drift are the dominating factors determining snow distribution and accumulation. The distribution of snow depths in such areas is consequently characterized by a high spatial variability that is difficult to evaluate and quantify, but is at the same time of high interest for avalanche forecasting. For example, the amount of snow present in avalanche starting zones is a key element for evaluating avalanche hazard. In addition to the complex numerical wind field models, Winstral et al. (2002) developed a terrain-based parameter to describe the wind effect on snow distribution. Their terrain-based parameter characterizes the wind scalar and quantifies the degree of shelter or exposure of a grid point provided by the upwind terrain. In previous studies, the parameter has shown to qualitatively predict snow redistribution with good reproduction of spatial patterns and to be a statistically significant predictor of snow depth (Winstral et al., 2002; Schirmer et al., 2011; Payer, 2012). The parameter has failed, however, to quantitatively describe the snow redistribution, and the statistical correlation between measured snow depths and the terrain-based parameter is generally poor (Schirmer et al., 2011; Payer, 2012). In our study we identify the sources of poor statistical correlation between snow heights and terrain-based parameter. We then show how the results of the terrain-based parameter calculated from a snow surface model differ from the results that are based on a digital terrain model obtained from a snow-free surface. Additionally, we show results of wind field simulations with the program ARPS. We used the program to assess the flow field in the research area and compare the results to patterns predicted by the terrain-based parameter and actual snow redistribution patterns.

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2 STUDY SIDE

The site of our research is the Col du Lac Blanc in the French Alps, near Grenoble and the ski resort Alpe d'Huez. The pass is north–south oriented and due to the surrounding topography, the pass can be considered to be a natural wind tunnel (Vionnet et al., 2013). 90% of the observed winds blow from the north–east or south. The Col is an area particularly suited for our study, for several reasons: a) the constant wind direction, b) the presence of three automatic weather stations (AWS) located around the pass, and c) the availability of TLS data from several surveying campaigns (Naaim-Bouvet et al., 2013)

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Our research area is divided into two main sectors, north and south, covering 530 x 320 m and 450 x 280 m (Figure 1). The weather station providing the wind data for our research is located near the southwest-corner of the north sector. Additionally, there is a smaller sector in the south, covering 200 x 100 m, and referred to as south sector (II) henceforth (Figure 1). The south sector (II) has a pronounced, approximately 10 m high terrain edge we used for more detailed studies described in forthcoming sections of this paper.

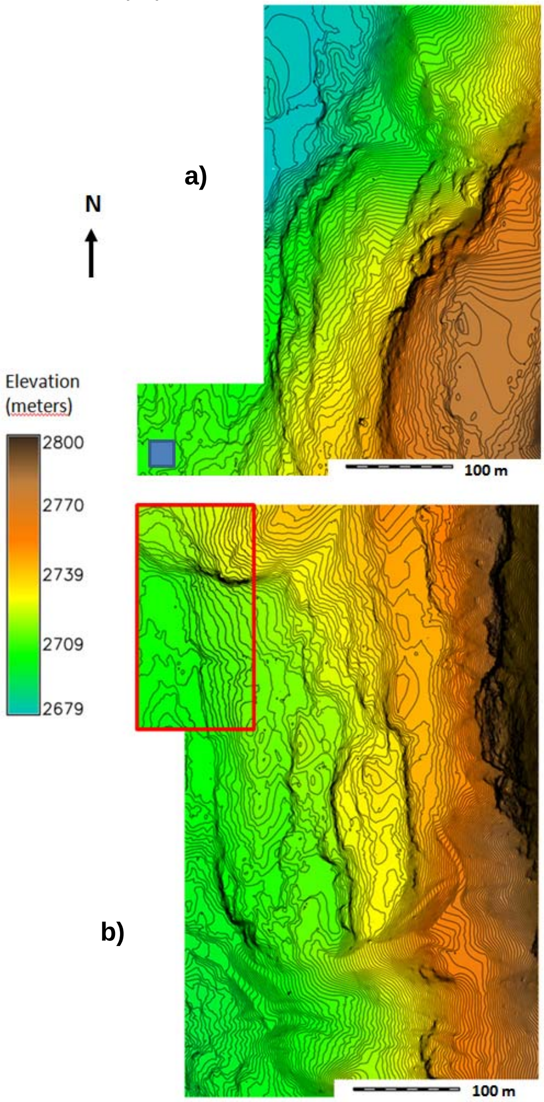

Figure 1. a) North and b) south sector; the blue square in the north sector marks the weather station, and the red area in the south sector marks the south sector (II).

3 METHODS

3.1 *Winstral terrain-based parameter*

Winstral et al. (2002) developed a terrain-based parameter to describe the wind effect on snow distribution. Their method avoids the computational efforts and difficulties of physical, numerical models. The terrain-based parameter, S_x, characterizes the wind scalar and quantifies the degree of shelter or exposure of a grid point provided by the upwind terrain. All cells along a vector originating from the cell of interest are examined for the cell providing the maximum topographic shelter, and return the slope (in degrees) between this shelter-defining cell and the cell of interest. Negative S_x values indicate exposure, positive values indicate shelter. Details on the algorithm are given in Winstral et al., 2002.

3.2 Terrestrial laser scan (TLS) data

In snow and avalanche research, terrestrial laser scanning (TLS, Figure 2) is used increasingly to accurately map snow depths over an area of several km². Laser scanners emit a pulse of light in the near-infrared spectrum. The pulse hits the terrain or snow surface and is reflected. A photodiode in the scanner detects the returning pulse, and determines the distance to the target from the travel time of the pulse. The data from the reflected pulses are saved in a point cloud, which then is interpolated into a digital snow surface or digital terrain model (Prokop, 2008; Prokop and Panholzer, 2009). Prokop (2008), Prokop et al. (2008), and Grünewald et al. (2010) report mean deviations between TLS data and reference tachymetry measurements of 0.04 - 0.1 m for target distances reaching 500 m, depending on the conditions and the laser used.

We used TLS snow data to obtain precise quantitative information about snow depths and snow redistribution. These data are derived by subtracting rasters from different scan campaigns. Then we correlated the snow depth and distribution data with the results of the terrain-based parameter and also compared the measured pattern of snow redistribution with wind-field simulations.

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Figure 2. Laser scanning at the Col du Lac Blanc. The north sector is visible in the background.

3.3 Spatial identification of areas with poor fit in GRASS GIS 7

The extension r.regression.multi in GRASS GIS developed by Markus Metz, calculates linear regressions from raster maps. The algorithm used to solve the equations is a standard OLS (Ordinary Least Squares) with a Gaussian elimination method (Markus Metz, personal communication, 2013). We used this extension to spatially identify areas of poor fit between the terrain-based parameter and the quantitative TLS data. In our study, the explaining, independent variable (y) was the terrain-based parameter, and the dependent variable (x) was the change in snow depth.

3.4 ARPS

ARPS (Advanced Regional Prediction System) is a three-dimensional, atmospheric model for simulating microscale airflows (Xue et al, 2000; 2001). The code has been used by several authors in the past to investigate snow deposition patterns in complex mountain terrain (Mott and Lehning, 2010; Mott et al., 2010; Prokop and Delaney, 2010). We used the model to assess vertical wind components and speeds in the research area.

We applied a horizontal resolution (dx/dy) of 1 m for the north sector. The larger grid of the south sector we re-sampled to 2 m resolution. In the past, grid resolutions of 5 m or more were used (Mott and Lehning, 2010; Prokop and Delaney, 2010; Schirmer et al., 2011). In our case, however, such a grid size would have lead to a partial loss of terrain features where differences between snow heights and terrain-based parameter occur.

The vertical grid spacing (dz) in both modes varies between 1 m near the ground and increases to 10 and 20 m, and finally 50 m in the upper layers of the atmosphere. This spacing results in 232 vertical sounding levels, with an upper boundary at 5900 m. We calculated the input wind velocities with the log wind profile, assuming 2 m/s wind velocity 10 m above the ground, and constant velocities from 1000 m above the highest point in the input terrain model. We used a constant aerodynamic roughness length of 0.01 m, following the work of Mott and Lehning (2010) and the measurements of Doorschot et al. (2004) and Stössel et al. (2010). The simulation time for the models was 30 seconds. In order to limit boundary effects, we extended the lateral boundaries of the south and north model 70 and 30 m. Without this measure, some areas of interest would have been located close to the model boundaries.

4. RESULTS FROM A CASE STUDY

For a case study, we chose the time period between 17 and 28 February 2011. In this period winds were constant from north-northeast (Figure 3).

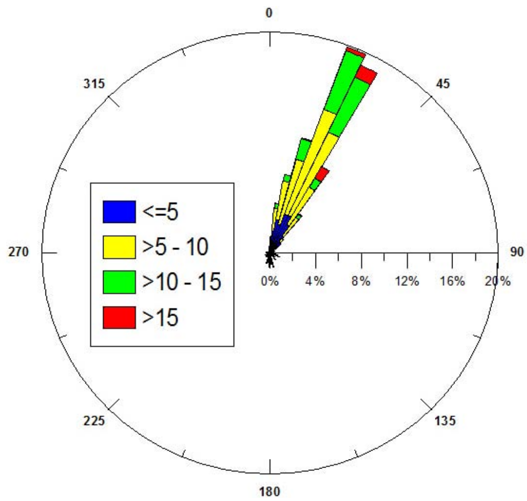

Figure 3: Wind direction (in °) and velocities (in m/s) registered at the Col du Lac Blanc test side, 17 - 28 February 2011.

4.1 Terrain-based parameter based on digital terrain model - spatial linear correlation

In a first step, we calculated, independently for the three sectors, the spatial linear regression between the measured changes in snow heights (between 17 and 28 February; Figure 4) and the terrain-based parameter calculated from a digital terrain model (DTM), and based on a wind direction of 25°. The terrain model has a grid resolution of 1 m and was obtained in the summer. Using a DTM is a practicable approach, because DTM are more readily available than snow surface models.

Analysis of spatial correlation shows that areas of poor correlations (high residuals) are in the lee of terrain edges (Figures 4 and 5). Here the parameter predicts high shelter very close to the terrain edges. The actual snow deposition occurs farther away from the edge, however (Figure 5). This shift between the terrain-based parameter and snow depositions results in a poor correlation between terrain-based parameter and actual differences in snow heights. The poor correlation also reflects the fact that snow distribution is a highly nonlinear function of wind speed (Schirmer et al., 2011). Figure 6 shows the plot of change in snow height versus the terrain-based parameter.

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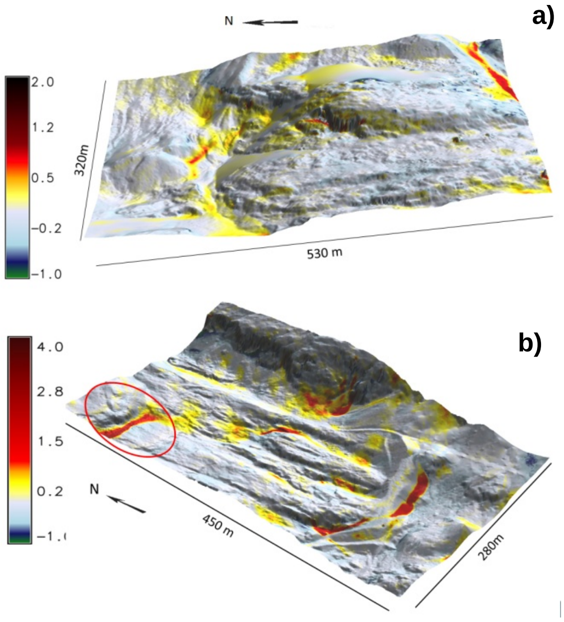

Figure 4. Residuals (in m) between measured snow redistribution (17 - 28 February 2011) and terrain-based parameter (wind direction 25°), for the a) north and b) south sector. The area marked red is shown in more detail in Figure 5.

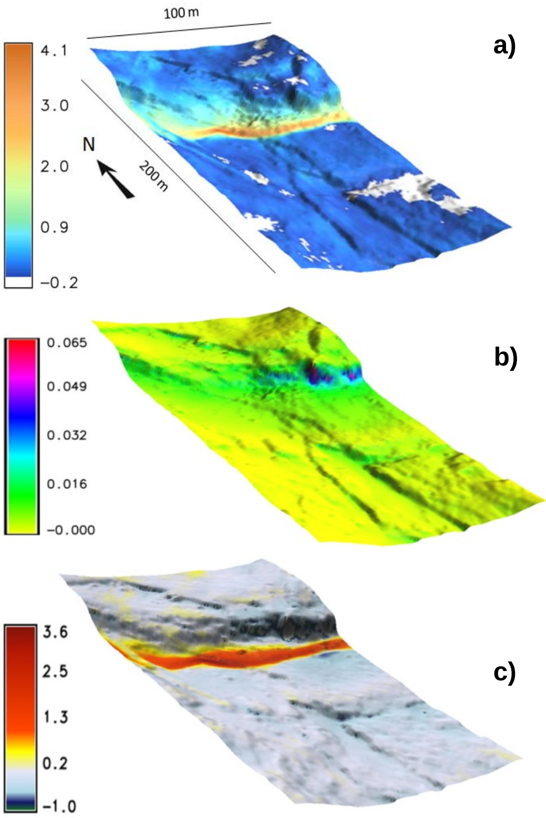

Figure 5. a) Snow redistribution due to wind between 17 and 28 February 2011 (in m), b) terrain-based parameter, and c) resulting residuals (in m), shown for the terrain edge in the south sector (II).

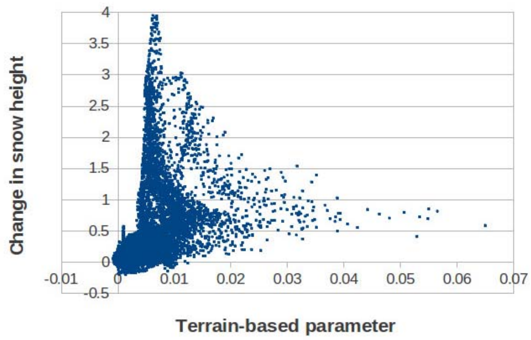

Figure 6. Plot of change in snow height (in m) versus the terrain-based parameter for the south sector (II), based on a summer DTM.

4.2 *Terrain-based parameter based on snow surface model*

Calculating the terrain-based parameter based on the snow surface, instead of the snow-free terrain surface, improved the correlation with snow heights in the lee of terrain edges, because the cells providing maximum shelter are now provided by the snow surface and located farther away from the terrain edges. The resulting correlation in the south sector (II) is now such that we can lay a regression line (Figure 7). The resulting coefficient of determination (R^2) is still low at 0.5. It should be noted, however, that this is the area of poorest statistical fit in the south sector (II) and R^2 value in other places would be higher. This approach requires the presence of snow surface data, which are often not available.

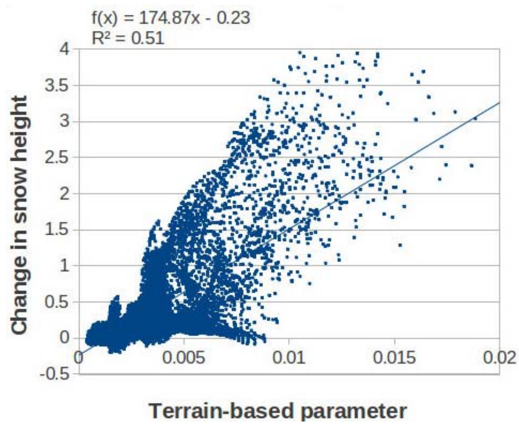

Figure 7. Linear regression between change in snow height and terrain-based parameter for the south sector (II), based on a snow surface model.

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4.3 Terrain-based parameter and absolute snow heights

The case study above looks at a short time stretch with winds of constant direction and fairly high velocities. When we correlate absolute snow heights for 28 February 2011 with the terrain-based parameter (based on summer DTM; wind direction 25°) a similar correlation pattern emerges, however (Figure 8).

This observation corresponds to the work of other authors (Prokop and Delaney, 2010; Schirmer et al., 2011), who found that single storm events from prevailing wind directions produce snow accumulation patterns similar to the absolute seasonal snow depth distribution.

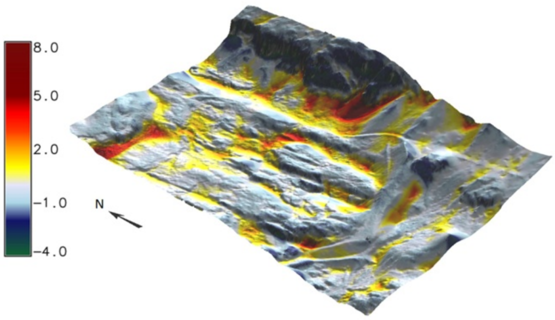

Figure 8. Residuals (in m) between terrain-based parameter and absolute snow depths on 28th February 2011, shown for the south sector.

4.4 Comparisons with ARPS

Finally, we compared the results of ARPS simulations with results from the terrain-based parameter and assess its ability to reproduce spatial patterns of snow distribution. Figure 9 shows the patterns of a) measured snow redistribution between 17 and 28 February 2011, b) terrain-based parameter S_x (calculated based on summer DTM), and c) vertical wind direction simulated by ARPS for the south sector. The results from ARPS for the vertical wind direction are in three color bands: blue is upwind and red is downwind, while green indicates no vertical wind component. Note that because we compare patterns only in this case, stretched scales are applied for snow redistribution and terrain-based parameter instead of distinctive classes.

Downwind corresponds to wind-deceleration and consequently to snow accumulation. Positive S_x values correspond to shelter and hence also to snow accumulation. Figure 9 shows a good agreement between the ARPS results and the terrain-parameter, and shows how both are able to reproduce patterns of snow redistribution.

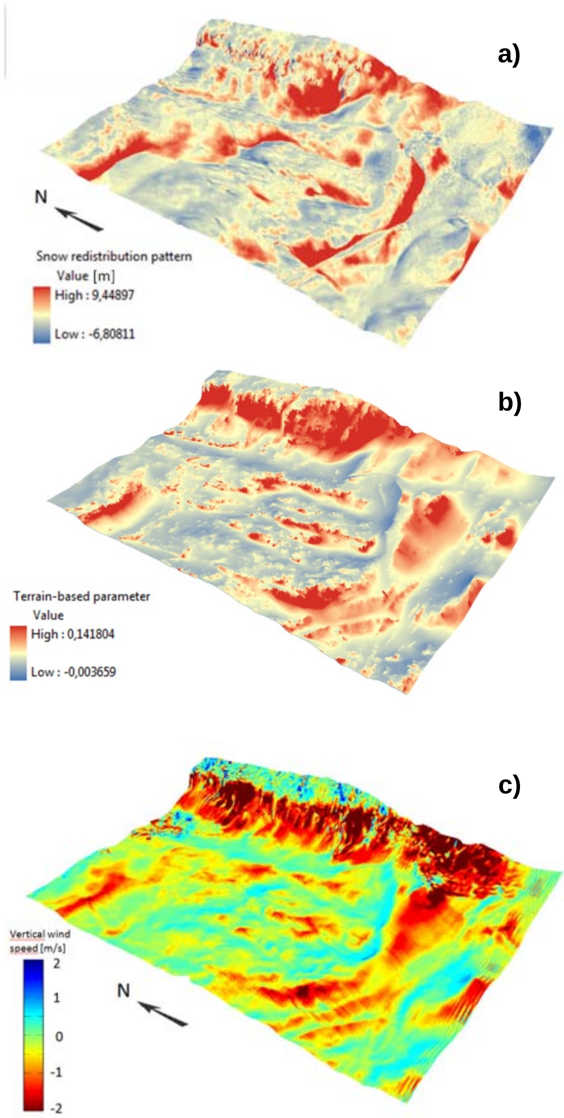

Figure 9. Comparison of patterns of a) measured snow distribution (in m), b) terrain-based parameter, and c) vertical wind speeds (in m/s) simulated by ARPS for the south sector.

5 CONCLUSIONS

We identified areas of poor spatial correlation between terrain-based parameter and measured snow redistribution for the Col du Lac Blanc research area. These areas are in the lee of terrain edges, where a shift occurs between the locations of maximum shelter predicted by the terrain-based parameter and the actual maxima of snow-redistribution due to wind. Using a terrain-parameter based on the snow surface improves the results. In this case, we could derive reasonable regression between the change in snow height and terrain-based parameter. The code ARPS has shown to be able to a) yield results comparable to the terrain-

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based parameter and b) reproduce patterns of snow redistribution.

Further work is required to improve the parameter's ability to quantitatively describe snow redistribution; the identification of areas with poor correlation between the parameter and snow depths is an important step.

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