ASSESSMENT OF MOUNTAIN SNOW TRANSPORT BASED ON MEASURED WIND AND SIMULATED SNOW COVER

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ABSTRACT: A local to regional assessment of transported snow during snow storms or subsequent periods of strong winds is a prerequisite to reliably predict avalanche danger. Despite the fact that it has received continuing attention for decades, the problem of quantifying snow transport persists. Systems from point measurements to full three-dimensional simulations are in operation but all have their respective weaknesses. We present a new drift index, which has been tested and operated with some success in Switzerland. The index requires input from a wind-sheltered automatic weather station and an additional wind measurement at a wind-exposed site. Using the snow cover model SNOWPACK, the meteorological data is extrapolated to the four main expositions and snow cover development is calculated for these expositions. Depending on the measured wind direction and speed, a threshold condition for snow erosion at the upwind exposition is tested: if the wind is strong enough to erode the current snow at the surface of this exposition, the snow layer is eroded, transported and deposited onto the downwind exposition. With this scheme, the virtual, "representative" snow cover on the four main expositions in the vicinity of the meteorological stations are reconstructed for the course of the winter. Drifting snow periods are reasonably well detected and a quantitative information on snow deposition in lee slopes is possible. Compared to earlier versions of the index, which had been based on flat field simulations of SNOWPACK, the new index no longer overestimates intensity and duration of blowing snow events.

KEYWORDS: Drift Index, Lee Slope Loading, Avalanche Warning, SNOWPACK, Snow Cover Simulation

1. INTRODUCTION

Snow transport is a major factor in determining the local avalanche danger. For the purpose of avalanche warning, snow transport is usually assessed by visual inspection of blowing snow clouds over mountain ridges or other subjective observations. A few measurement devices have been designed (e.g. Chritin et al., 1999), which measure the transport rate at a single point. They are not widely used because a point transport rate is difficult to interpret and the devices have calibration problems (Lehning et al, 2002). Therefore, a different approach is to use model descriptions of drifting and blowing snow to describe snow transport over mountain ridges and loading of lee slopes by wind. While first attempts have been made to model the full three-dimensional distribution of snow deposition and erosion on a scale relevant for avalanche warning (Gauer, 2001), for operational purposes, a simplified approach is advantageous. To our knowledge, the only two operational systems of snow transport assessment are the French SCM chain with the SYTRON blowing snow model (Durand et al., 2004) and the Swiss snow drift index based on SNOWPACK model simulations (Lehning et al., 2000). However, due to systematic weaknesses, the index had limited success and acceptance in the avalanche warning community. We therefore have continuously worked to improve the index and present a new drift index algorithm, which is still based on measured wind and simulated snow cover properties but introduces virtual slopes for four expositions. Because the index now has distinct erosion and deposition slopes, it does no longer overestimate the duration of drift events. Also, the information on past snow redistribution is no longer lost with each new snow fall.

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2. DRIFT INDEX ALGORITHM AND SET-UP

The mass transport calculation follows the algorithm presented in Lehning et al. (2000). First, a local threshold friction velocity, u_{*th}, is determined (Schmidt, 1980) based on the local snow characteristics as calculated by the snow cover model SNOWPACK (Lehning et al., 1999):

$$u_{*th} = \sqrt{\frac{A\rho_i g\, r_g (SP+1) + B\sigma N_3 \frac{r_b^2}{r_g^2}}{\rho_a}}, \quad (1)$$

where ρ_i and ρ_a are the ice and air density, respectively, *SP* is the sphericity of the model grains, r_g and r_b are the grain radius and bond radius, respectively, N_3 is the grain coordination number, *g* is the acceleration due to gravity and σ is a reference shear strength set to 300 Pa. Our wind tunnel verification studies (Clifton et al., in press) and field investigations have shown that the two geometrical constants *A* and *B* need to be set to 0.02 and 0.0015 respectively. From the threshold friction velocity, a saltation mass transport rate, *Q* [kg m^{-1} s^{-1}], can be determined (Sørenson, 1991):

$$Q = 0.0014\rho_a u_*(u_* - u_{*th})(u_* + 7.6u_{*th} + 205), \quad (2)$$

where u_* is the friction velocity derived from the measured wind speed. This saltation model is used here as it has proven to deliver good results when compared to measurements (Doorschot and Lehning, 2002). It now replaces the earlier implementation following Pomeroy and Gray (1990). The local snow mass transport rate is then translated into a lee-slope loading.

The operation of the SNOWPACK model in the Swiss Alps is based on now more than 120 automatic weather stations, which all consist of a wind and one to three snow stations. The wind station is at a ridge or summit and the snow station(s) is (are) at representative flat-field site(s) close to the wind station. The automatic weather stations are at an altitude range between 2000 and 3500 m a.s.l. The measured wind at the wind station is combined with the simulated snow at the snow station to calculate a virtual mass transport rate and an associated drift index. This combination has proven to be problematic because the snow station is chosen to be at a representative snow site, where snow deposition or erosion due to wind should not be dominant. Therefore, the snow at the snow station is in reality never exposed to the high wind speeds measured at the wind station. Accordingly, drifting and blowing snow does not influence the surface of the modeled snow and an undisturbed surface is exposed, which in turn is used to calculate the threshold wind speed as discussed above. This leads to an overestimation of the duration and strength of modeled blowing snow events since in reality all moveable snow may have already been eroded or compacted by the wind.

The new drift algorithm solves this problem by introducing four virtual slope expositions with a slope angle of 38 °. For the four expositions north, east, south and west, separate snow cover simulations are introduced. Per calculation time step the following algorithm is applied:

1) From the measured wind direction at the wind station, the windward and lee expositions are determined.
2) The threshold wind speed for the windward exposition is determined.
3) If the measured wind is higher than the threshold, the transport rate is calculated as explained above.
4) The transport rate then determines the amount of snow eroded at the windward exposition.
5) If a complete SNOWPACK snow layer is eroded, the threshold conditions are re-evaluated not before the next time step for the new snow layer now exposed.
6) The eroded mass and the density of the eroded layer are stored and then deposited at the lee exposition.

Note that snow from snowfall is equally deposited at all expositions and the flat field. Since freshly deposited snow is very easily eroded, this leads to the fact that during snow fall snow mass rates are usually high.

Finally, the wind-driven snow masses are cumulated over 24 hours irrespective of exposition to yield a representative snowdrift index for lee slope loading.

3. NORMALIZATION OF WIND SPEED

Another complication with the combination of wind and snow stations as described above is that the relationships between wind and snow stations are very site-specific. Since the snow transport rate is approximately a function of the wind speed to the third power, small changes in the wind speed will cause large changes in the snow mass transport rate. As a result, plotting the simulated drift index on a map of the Swiss Alps, very inhomogeneous patterns will show up, depending more on the wind statistics of the individual wind stations than on the true local to regional snow transport. Therefore, we need to normalize the wind speed measured at the wind station to allow individual stations to be compared. A normalization based on the mean and the standard deviation has proven to be effective: For every station, a correction factor, f_s, is calculated based on a time series of at least one complete winter season:

$$f_s = \frac{\frac{1}{n}\sum_{i=1}^{n}(\bar{v}_i + \sigma_i)}{\bar{v}_s + \sigma_s}, \tag{3}$$

where n is the number of stations in a region, the subscript s stands for a particular station, $\bar{v}$ is the time-average of the wind speed measurements and σ the corresponding standard deviation. Values of f_s have been found to vary between 0.7 and 1.4, with many values being close to unity.

4. RESULTS AND DISCUSSION

In this section, we present first results from the new drift index. Figure 1 shows the comparison between the new drift index described here and the original version (Lehning et al., 2000), exemplified at the automatic weather station Bernina. This is an extreme example in the sense that the wind station has very high average wind speeds. Therefore, the old, un-scaled drift index gave always unreasonably high values. The wind speed scaling factor (Eq. 3) for the station is f_s = 0.8 and the non-linear effect on the mass transport is clearly visible. The lower curve gives reasonable values of estimated drift and the shorter periods of simulated drift correspond better to the corresponding observed periods.

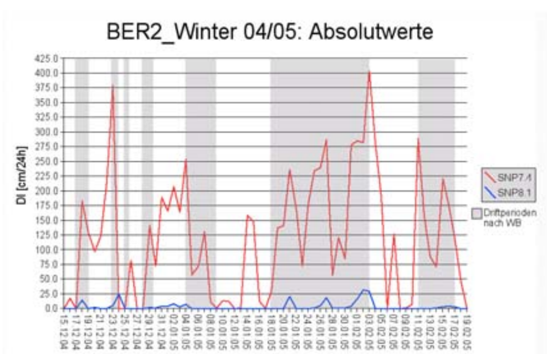

Figure 1: Drift index from the automatic weather station Bernina during the winter 2004/2005 for the old (SNP7.4) and the new (SNP8.1) drift index. The grey areas show times when drifting snow was reported by local observers.

Local observers report snowdrift in three classes. If we associate “no reported drift” with drift index values below 5 cm, the class “low” with a drift index between 5 and 20 cm, the class “medium” with 20 to 50 cm and the class “high” with drift index values larger than 50 cm, we can make a semi-quantitative verification. Figure 2 shows this comparison for the automatic weather station Davos Hanengretji, where a very reliable local observer is operating. In 54% of all cases, the drift class has the same value both in observation and simulation. In 13% of all cases drift was both observed and simulated but the classes differed. This gives a total success rates of 67%. This analysis was done for five automatic weather stations and total success rates ranged from 64% to 77%.

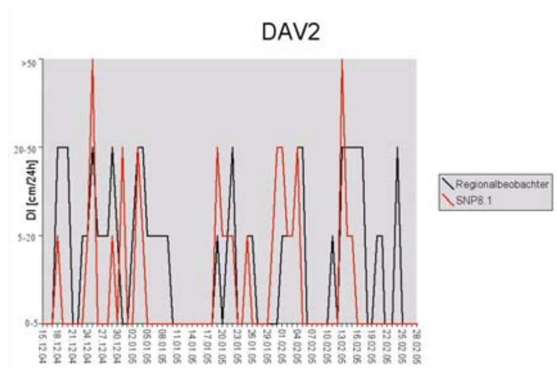

Figure 2: Drift index (SNP8.1) from the automatic weather station Hanengretji during the winter 2004/2005 and observed drift (Regionalbeobachter) as reported from a local observer.

In addition to evaluating the time series of the drift index at individual stations, the avalanche warning service is also interested to see which areas are particularly affected by drifting snow. Figure 3a is a graphical representation of the observed drift reports for all of the Swiss Alps on December 16, 2005. The magnitude of the drift is represented by the radius of the circles and the segments show the exposition of loaded slopes. The two digit number on the plot only shows the altitude above which snowdrifts are observed, e.g. +18 means that drift has been observed above 1800 m a.s.l. Figure 3b gives the drift pattern as predicted by the SNOWPACK drift index, where the magnitude of the drift is given by the height of the bar. The comparison shows that large drift values are predominantly observed in the eastern part of the Swiss Alps. One day later, on December 17, large drift values are observed (Figure 4a) and simulated (Figure 4b) for all of the Swiss Alps.

5. CONCLUSIONS AND OUTLOOK

We presented an improved drift index, which is used to estimate drifting snow and lee slope loading to support avalanche forecasting. The index has an improved process representation and uses virtual slopes and expositions to allow erosion in windward and deposition in lee slopes. The snow cover model SNOWPACK provides the framework of the drift simulations and simulates the snow cover development on the windward and lee slopes. The new index can represent local to regional blowing and drifting snow events when compared to observations and distinguishes between regions of high and low drifting snow. In the future, we will continue to validate the new drift index and investigate further, whether the simulation of the virtual slopes can also be used to estimate local to regional snow cover stability (Bellaire et al., this issue).

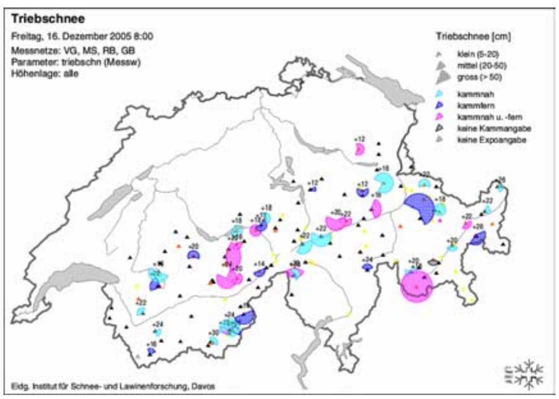

Figure 3a: Plot of observed drift over the Swiss Alps on December 16, 2005 as reported by experienced observers.

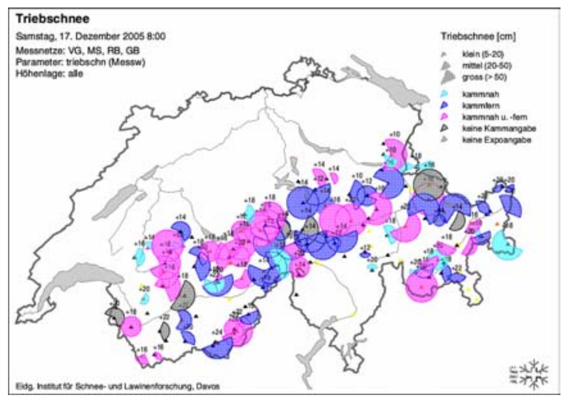

Figure 4a: Plot of observed drift over the Swiss Alps on December 17, 2005 as reported by experienced observers.

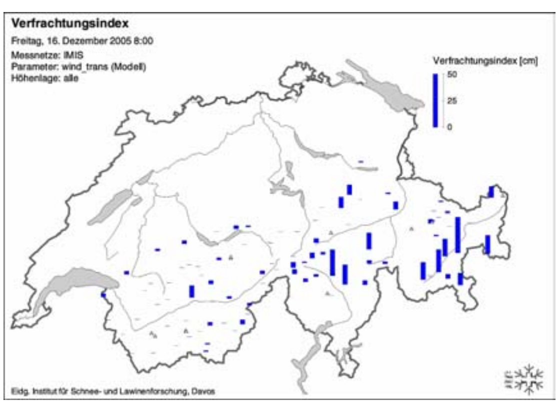

Figure 3b: Plot of simulated drift over the Swiss Alps on December 16, 2005.

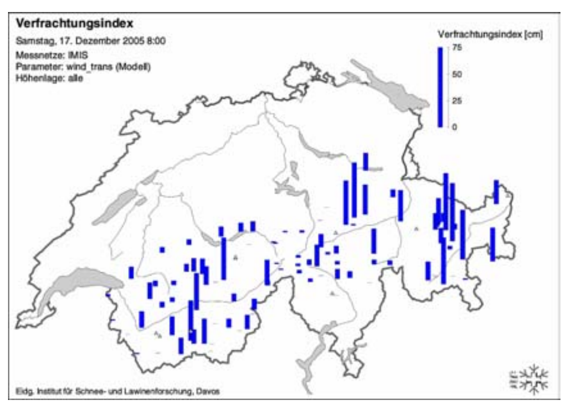

Figure 4b: Plot of simulated drift over the Swiss Alps on December 17, 2005.

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