Understanding snow transport processes shaping the mountain snow-cover

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ABSTRACT: In alpine terrain the snow cover is heterogeneously distributed as a result of wind and precipitation interacting with the snow cover at various scales. The aim of this study is to achieve a better understanding of snow deposition and drifting and blowing snow at different scales, analyzing major drift events of an accumulation period. We want to examine snow deposition features at ridge scale as well as at smaller scales, in particular we investigate two huge cross-slope accumulation zones. High resolution (10 m) wind fields were computed with the atmospheric model Advanced Regional Prediction System (ARPS) and used as input for a model of surface processes in alpine terrain (Alpine3D) in order to quantify preferential deposition and redistribution of snow via saltation and suspension. We used a unique data set consisting of a high density network of automatic weather stations and Terrestrial Laser Scanning measurements of snow depth to validate the model results. The snow distributions were measured in a high spatial resolution at the end of the accumulation season 2007/2008 and before and after major snow drift events during the season 2008/2009. The results show that the observed snow deposition patterns have their correspondence in the mean flow field computed for those small scales.

KEYWORDS: spatial variability, small scale wind fields, snow transport processes

1 INTRODUCTION

The mountain snow cover is shaped by snow transport processes. The flow field adapts to the complex topography and initiates snow transport processes. Especially in the highly complex terrain of the European Alps the associated redistribution of snow leads to a strong heterogeneity of snow depths and snow cover properties (e.g. Föhn and Meister, 1983). The interaction of wind and topography in combination with snow fall additionally promotes the enhanced snow loading in leeward slopes due to preferential deposition of precipitation (Lehning et al., 2008). Together with the spatially and temporally varying energy balance these processes lead to a spatial variability of snow stability as well which represents the main challenge in avalanche forecasting (Schweizer et al., 2007). Furthermore, the inhomogeneous snow cover leads to large uncertainties in estimating snow water storage.

There exist multiple model approaches trying to physically describe saltation and suspension as the main mechanisms for moving snow (Mellor, 1965, Male, 1980, Schmidt, 1980, 1986, Pomeroy, 1998; Pomeroy and Gray, 1990; Lehning and Fierz, 2008).

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More complex models were built which also involve the solution of complex 3-D wind fields over high-resolution grids (Gauer et al., 2001; Liston et al., 2007; Lehning et al., 2008). Recent studies show that atmospheric models can be used to reproduce characteristic flow features of the mean wind field, such as crest speed-ups, flow separation and blocking of flow over pronounced topographical obstacles (Raderschall et al., 2008; Mott et al., 2008; Dadic et al., 2009; Bernhardt et al., 2008).

Previous studies of drifting and blowing snow often suffered from an insufficient measurement density of snow depth. New technologies like terrestrial laser scanning (TLS) permit the survey of snow depth variability in a very high resolution (Prokop et al., 2008). Dadic et al. (2009) investigated snow accumulation on a glacier and showed that accumulation maxima as measured by airborne LiDAR are caused by the mean flow field on a scale of 30 m. The deposition pattern at a smaller scale has not been subject to this investigation.

In this work we therefore discuss one snow fall event with wind speeds high enough to initiate snow transport processes and thus redistribution of already deposited snow at a scale of 10 m. We want to examine the processes on the ridge scale as well as on smaller scales. We investigate diverse terrain features present at the Wannengrat area and a focussed analysis of two huge cross-slope accumulation zones. We expect the mean local flow patterns to give us insight into the formation of local deposition maxima due to snow drift as well as ridge scale deposition which is mainly driven by preferential deposition of precipitation.

2 DATA AND METHODS

The study site is the Wannengrat catchment, located in the region of Davos, Switzerland (Fig. 1). The whole investigation area is located above tree line at altitudes ranging from 2000 m to 2700 m a.s.l. The area is characterized by very complex terrain and shows topographical features such as ravines, ridges, pronounced ditches and bumps, luff as well as lee slopes.

We want to investigate the spatial and temporal variability of the snow depth distribution intensively for the accumulation in 2008/2009. The snow-cover was measured with a Terrestrial Laser Scanner (TLS) before and after eight snow fall and snow drift events with a high spatial resolution. This data set gives us an unprecedented possibility to analyse the spatial heterogeneity of snow depths after snow drift and snow fall events as well as its evolution during the accumulation period.

Wirz et al. (this issue) used the same dataset to analyse the spatial patterns of snow accumulation in a rock face. Grünewald et al. (this issue) analyzed the spatial variability of snow depth, SWE and melt rates for the winter 2007/08 ablation season using a dataset obtained with the same method.

The Wannengrat area is equipped with seven automatic weather stations. Meteorological data were used for meteorological forcing of the models. We computed the initial adaptation of the flow field to the complex terrain using the non-hydrostatic and compressible atmospheric model ARPS (Advanced Regional Prediction System) (Xue et al., 2004).

We used the calculated wind fields as an hourly input for the Alpine3D model based on the measured wind parameters and calculated the preferential deposition and redistribution of snow via saltation and suspension (Lehning et al., 2008).

Finally we simulated all periods measured by TLS with the Alpine3D model, initiated by three-dimensional wind fields characteristic for the respective events. In order to minimize the computational efforts we calculated a set of wind fields in advance.

We selected five sub areas of interest which were characterized by specific patterns of snow distribution: Wannengrat north-east slope (A), Wannengrat north-west slope (B), Vorder Latschüel (C), Chilcher Berg (D) and the south-west rock face of Chüpfenflue (E). The areas are indicated by the capital letters A-E in Fig. 1.

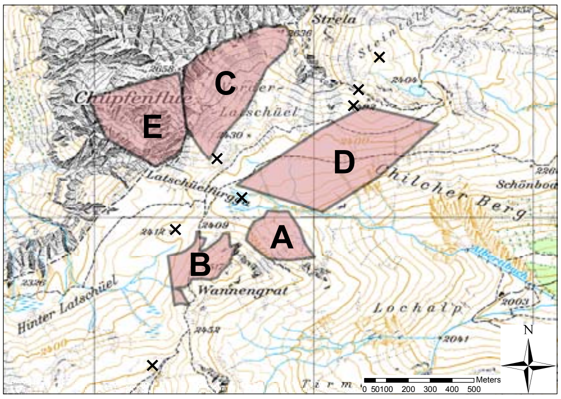

Figure 1: Weather stations in the study area indicated by black crosses and sub areas of interest indicated by capital letters: A= Wannengrat north-east slope; B=Wannengrat north-west slope, C= Vorder Latschüel, D=Chilcher Berg; E= southwest rock face Chüpfenflue.

3 RESULTS

3.1 *Observed features of snow deposition*

Measurements of snow distribution showed that the pattern of enhanced erosion/depositions zones after snow drift events were rather similar after all drift events under the prevailing wind direction north-west. In the Wannengrat area the inflow direction is north-west for cold front passages with precipitation and high winds. Thus we tried to investigate predominant snow drift patterns which developed under north-west wind conditions. In Fig. 2 and 3 measured snow depth changes are shown for two snow fall events in March 2009.

At the ridge scale the largest amount of snow was deposited in the Vorder Latschüel (C) and in other leeward slopes of the catchments. Reduced deposition and enhanced erosion of snow was measured in wind-exposed sides of the ridge (i.e. Wannengrat north-west slope, B).

Previous studies of Lehning et al. 2008 showed that homogenous depositions are likely to be caused by preferential deposition whereas smaller scale deposition features are formed by pure snow drift.

The small scale topography of the Wannengrat region has a big influence on the local wind field and thus on snow transport and deposition of snow. This effect is impressively demonstrated by the continuous development of two large cross-slope accumulation zones in the lee of cross-slope ridges located within the Wannengrat north-east slope (A). After every surveyed snow drift and snow fall event in these zones snow dune-like features grew significantly. In contrast the Wannengrat north-west slope (B) is exposed to stronger winds and therefore experienced enhanced snow erosion of already deposited snow due to snow drift processes.

The Chilcher Berg (D) had average snow accumulation. The spatial variability of the snow depths within Chilcher Berg valley was dominated by snow filled ditches and reduced deposition of snow on smaller-scale ridges (moraines).

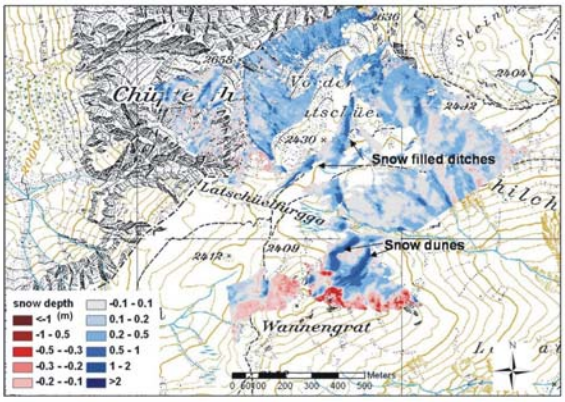

Figure 2: Measured distribution of snow depth change during the snow drift and snow fall period in mid of March 2009 (9 – 14 March 2009).

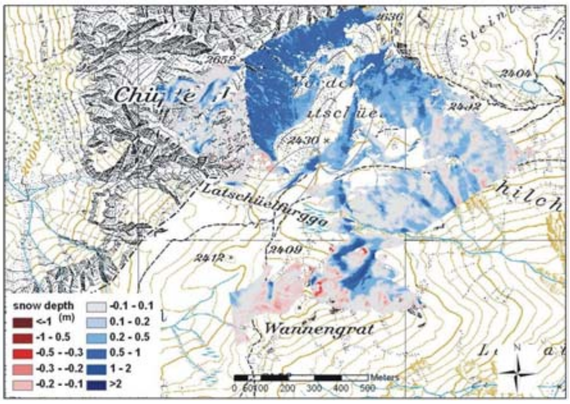

Figure 3: Measured snow depth changes after the snow fall event end of March 2009 (23 – 27 March 2009).

The Vorder Latschüel (C) is a large-scale wind protected gully. The modelled wind velocities (Fig. 4) were quite low for this area and the spatial distribution showed a small spatial variability. Due to crest speed-up very high wind speeds were modelled for the ridge crest of Chüpfenflue. The Vorder Latschüel experienced enhanced deposition of snow with a comparatively homogeneous snow loading primarily caused by preferential deposition of precipitation. At the ridge crest huge cornices were formed during the winter.

The south-west rock face (E), showed in almost all periods snow deposition above average, but less than the Vorder Latschüel (C). The spatial variability of the snow-cover was characterized by enhanced snow deposition in small gullies and smaller snow depths on the ridges between them.

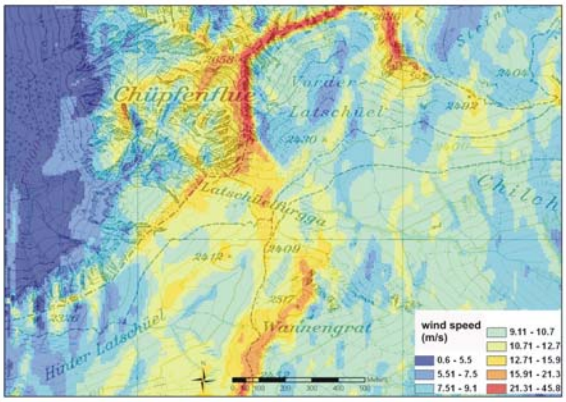

Fig. 4: Modelled distribution of wind velocity for a north-westerly wind situation (strong wind event)

3.2 *Snow transport simulations*

Snow transport processes were simulated for all snow drift and snow fall events measured during winter 2008/2009. In Fig. 5 the modelled snow depth change during the drift and snow fall period from the 9 until the 14 March 2009 is shown. In this period the wind speeds were strong enough to initiate saltation and therefore erosion and redistribution of already deposited snow.

It is clearly visible in Fig. 5 that the main zones of enhanced snow deposition and snow depletion were captured by the snow transport model.

At the Chüpfenflue ridge crest the developement of a huge cornice was modelled. In the Vorder Latschüel (C) strong increase in snow depth of 0.5 – 1.0 m which was distributed very homogenously over the slopes within this area was simulated. Model runs just regarding preferential deposition without drift processes assumed that these features were caused by preferential deposition. On the south-westerly rock face (D) the influence of the topographical structures, i.e. the channels, are clearly shown in modelled and measured snow deposition (Fig. 2, 3 and 5). The main erosion areas developed at the Wannengrat north-west slope (B) and the ridge crest of Chüpfenflue which were exposed to strong winds (Fig. 4) due to crest speed-up effects. Further erosion areas were modelled at the top of a smaller-scale ridge, located at Latschüelfurgga and the moraine at the foot of the Vorder Latschüel (C). Especially at Latschuelfurgga strong wind velocities (Fig. 4) were modelled. For ditches associated with the ridges and the moraine (Fig. 2, 5) measurements were available and showed enhanced snow accumulation (marked in Fig. 2 and 5) which have also been simulated. Measurements and simulations showed an enhanced accumulation of snow in these local depressions.

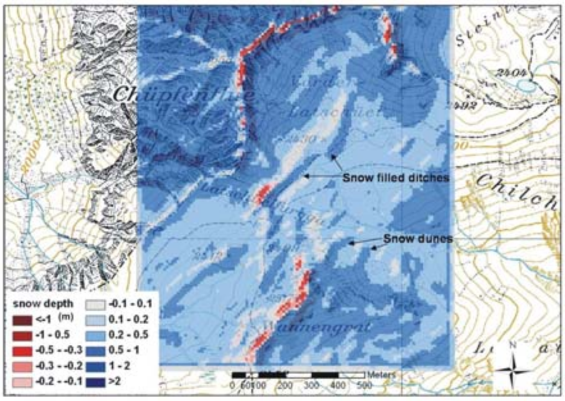

Figure 5: Modelled snow depth change after snow fall event in March 2009 (9 -14 March, 2009)

The simulation also captured the development of the two snow dune like features in Wannengrat north-east slope (A).

In Fig. 6 we show four transects which cross the two snow dune like features. It is visible for all transects that the snow transport model calculated two distinct peaks of snow accumulations. The first peak of snow accumulation is located a few meters in front of the measured peak of snow depth change. The second peak is less pronounced than the measured maximum of snow depth. In Fig. 7 we show transect 2 in more detail and compare it to the corresponding transect of topography in order to relate the location of the development of the snow dunes to topography. Measurements and simulations show that the snow dunes developed in the lee of cross-slope ridges causing a significant increase of the slope angle. Modelled snow accumulations are located closer to the top of the cross-slope ridges.

To quantify the results we calculated the Pearson's Coefficient of Correlation at all four transects: The correlations between measured and modelled snow depth on the one hand and between measured snow depth and wind speed for two different wind fields on the other hand are shown in Fig. 8. The calculations showed very high negative correlations between measured snow depths and three-dimensional wind velocities for wind conditions with moderate wind speeds, as well as for strong wind conditions. These values indicated a strong dependence of snow depth distribution on the modelled mean wind field. The correlations between measured snow depths and modelled snow depths were quite low and strongly dependent on the location of the chosen transect. Transect 1 showed even a negative correlation between measured and modelled snow depth change. The low correlation was considered to be caused by the shift between modelled and measured maxima of snow depths. A shift of the first peak of modelled snow depth in x-direction would strongly improve the coefficients of correlations.

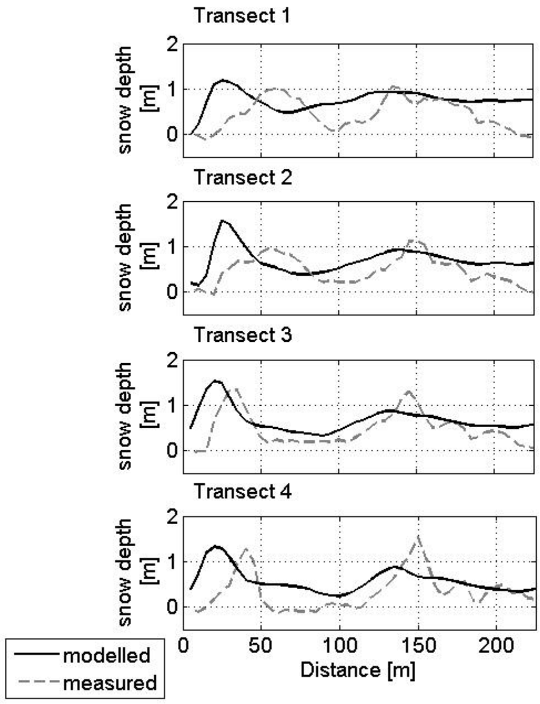

Figure 6: Four transect of modelled and measured snow depths crossing the snow dunes for period mid of March 2009.

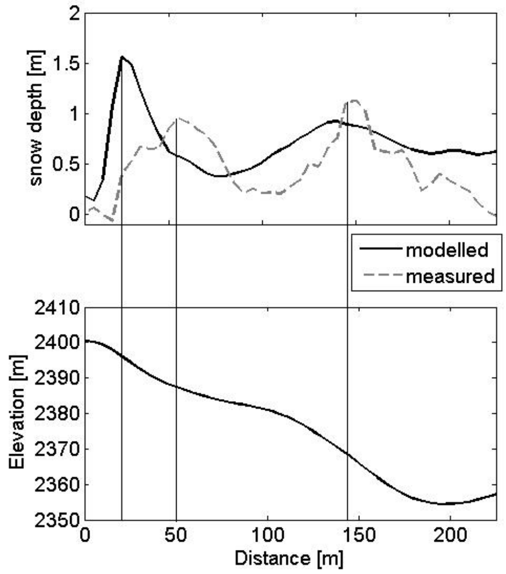

Figure 7: Modelled and measured snow depth changes at Transect 2 and the corresponding topography.

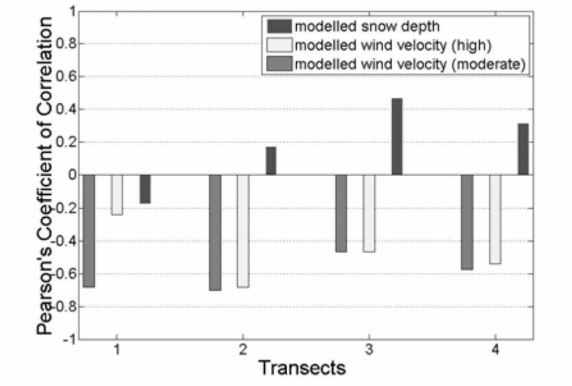

Figure 8: Pearson's Coefficient of Correlation of measured and modelled snow depth changes/ wind velocity (moderate and strong wind conditions) for the drift period 9 -14 March 2009.

4 CONCLUSION

The results of the Laser scanning measurement campaign in 2008/2009 gave us a detailed insight into the temporal and spatial variability of the snow cover at the Wannengrat region. Zones of accumulation and depletion could be identified and further investigated. The results of atmospheric and snow drift modelling showed that the mean wind fields, which are characteristic for the respective area, initiate snow transport processes leading to snow drift features consistently observed during the course of the winter season.

Tabler (1975b) tried to reduce the complexity of snow drift to an empirical and analytical relationship between topographical parameters, wind speed and transport rates of snow. This method could explain to some extend observed patterns of snow deposition. Smaller-scale deposition features such as the snow dunes, however, are caused by additional three-dimensional effects of the wind field. These additional flow features can only be calculated by an atmospheric model.

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