8.3 SUBLIMATION OF DRIFTING SNOW IN AN ALPINE CATCHMENT

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1. INTRODUCTION

Drifting snow sublimation amounts have never been measured in an uncontrolled environment and model estimates highly vary, e.g. 4% (Strasser et al. 2008) to 50% of snowfall (Bowling et al. 2004)). In the Alpine regions there is an interest in quantifying sublimation, as during Föhn storms drifting snow is observed at ridges, but deposition on the lee side is often only small (Wever et al. 2009).

Several physical drifting snow models have been developed that include sublimation. Xiao et al. (2000) give a comparison of four one-dimensional models. In all of these models, sublimation of drifting snow is accounted for. However, as they are only one-dimensional, advection effects can't be included. Examples of physically based three-dimensional drifting snow models are SnowTran-3D (Liston; Sturm 1998), the prairie blowing snow model (PBSM) (Pomeroy et al. 1993) and SYTRON3 (Durand et al. 2005). Feedbacks between sublimation and temperature and humidity of the air are not explicitly implemented in any of these models. Thermodynamic feedbacks have been studied by Dery et al. (1998) with a fetch-dependent blowing snow model. They found strong temperature decreases and significant increase of humidity near the surface due to sublimation. The sublimation process appeared to be self-limiting. A model which does not rely on the simplified fetch approach but includes advection processes and can be applied in complex terrain should give more insight in the sublimation process in Alpine regions.

In the Alpine region, few studies on drifting snow sublimation are available due to the complexity of the blowing snow and sublimation process in steep terrain and the often difficult field accessibility. Strasser et al. (2008) simulated drifting snow with SnowTran-3D for the Berchtesgarden National Park and found that drifting snow sublimation has a large spatial variability. At crests and ridges more than 1000 mm w.e. would sublimate within a season, being roughly 70% of the local winter snowfall. Averaged over the complete domain, only 4.1% of snowfall was lost to sublimation from turbulent suspension. This study shows the local significance of drifting snow sublimation in the Alpine region. However, it doesn't show where the deposition is mostly influenced by sublimation of drifting snow, nor how feedbacks influence the sublimation and (indirectly) deposition. Furthermore, the coarse resolution of the driving wind field (200 m) and the model formulation for drifting and blowing snow may have been inadequate for the terrain studied (Mott and Lehning, accepted for publication, 2010).

As mentioned, most models neglect the advection processes and the temperature and humidity feedbacks on sublimation of blowing snow. In this study, we focus on this process and quantify the several feedbacks which are neglected in other models. We will extend a sublimation model introduced by Wever et al. (2009), which was tested for ensembles of particles in a wind tunnel. The coupling of this model to a three-dimensional snowdrift model allows us to estimate the thermodynamic effects of sublimation. Furthermore, with a three dimensional model with a high resolution we will be able to reproduce the local effects on the snow cover in complex Alpine terrain.

We describe the model in section 2, and the Wannengrat catchment in section 3. In section 4, we present observations of our test period, in 5 we show and discuss our results and a conclusion is given in section 6.

2. MODEL

Alpine3D is a model that describes mountain surface processes with much detail (Lehning et al. 2006). It consists of several modules, including a physical snow cover model, (Lehning and Fierz, 2008), an energy balance and a drifting snow module. The drifting snow module is described by Lehning et al. (2008). Snow transport is calculated on the basis of mean flow fields. Previous studies, such as Mott et al.

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(2010), showed that deposition patterns can be explained with mean wind fields.

In Alpine3D, the mixture of suspended snow particles in the air is regarded as a continuous fluid and concentrations are calculated with an advection-diffusion equation. We assume steady-state over time steps of one hour and use mean flow wind fields of ARPS as input. Similar to the concentration equation, we now solve steady state equations of specific humidity and potential temperature and introduce drifting snow sublimation as a source (S) in the 3 steady state equations given below.

$$\frac{\partial}{\partial \vec{x}}\left(K_c \frac{\partial c}{\partial \vec{x}}\right) + \vec{u}_p \cdot \frac{\partial c}{\partial \vec{x}} = -S$$

$$\frac{\partial}{\partial \vec{x}}\left(K_q \frac{\partial q}{\partial \vec{x}}\right) + \vec{u} \cdot \frac{\partial q}{\partial \vec{x}} = \frac{S}{\rho_{air}}$$

$$\frac{\partial}{\partial \vec{x}}\left(K_\theta \frac{\partial \theta}{\partial \vec{x}}\right) + \vec{u} \cdot \frac{\partial \theta}{\partial \vec{x}} = -\frac{1}{\rho_{air} \cdot C_P}\left(L_v S\right)$$

K is the diffusivity coefficient [$m^2 s^{-1}$], c the concentration of suspended snow [kg m^{-3}], q specific humidity [kg kg^{-1}], θ the potential temperature [K], u the wind vector [m s^{-1}], L_v the latent heat of sublimation [J kg^{-1}] and ρ the density of the air [kg m^{-3}].

A difficulty in this setup is that sublimation is not only dependent on temperature, humidity and concentration; it also influences all of these variables. Therefore, we have to account for the feedbacks by calculating the steady state sublimation rate, which solves the three coupled equations. We iteratively solve the 3 steady state equations, until a steady state sublimation rate is found. Since drifting snow sublimation will cause a saturation of the air and a decrease of the concentration, steady sublimation is typically much smaller than the initial sublimation, which is calculated from unaffected concentration, temperature and humidity fields.

For the calculation of the sublimation, we use the expression of Thorpe and Mason (1966) for a single ice sphere (though we neglect the influence of solar radiation) and extend this to an ensemble of particles. Wever et al. (2009) showed that this approach is possible. The ensemble of particles used in most models follows a height dependent particle distribution (see e.g. Xiao et al. 2000). For such an ensemble we calculated the sublimation representative radius, which is the size at which the same concentration would cause the same sublimation as the ensemble of particles. Consistent with our steady state assumption, this radius is then assumed to be stable for one blowing snow situation (1 hour).

Apart from the mean flow fields, Alpine3D also needs meteorological observations. Results of the model include a snow distribution and a detailed snow stratigraphy.

3. WANNENGRAT FIELDSITE

All simulations in this study are done for the Wannengrat catchment. This is a small but highly complex catchment located near Davos in the SE part of Switzerland. It is equipped with 7 automatic weather stations, allowing us to get a detailed picture of the wind field. Furthermore, frequent terrestrial laser scans (Grünewald et al. 2010) have given us insight in the snow distribution patterns (e.g. Mott et al. 2010; Schirmer et al., submitted, 2010). An overview of the area is given in Figure 1.

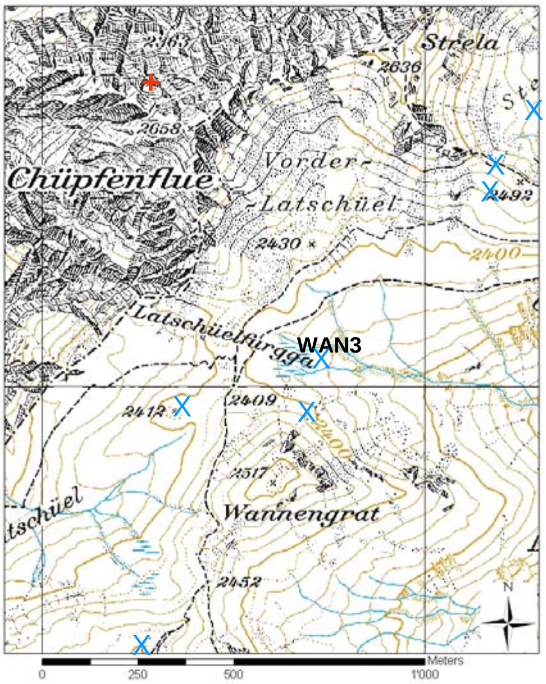

Figure 1 Wannengrat fieldsite near Davos. Blue crosses indicate permanent weather stations. Red + is a location selected for further analysis in section 5. Base map: Pixelkarte PK25 (1197) © swisstopo.

Within this area, wind mainly comes from west/northwest, with a strong speed-up over the steep west slope of Chüpfenflue and near the ridge of Wannengrat and very weak winds in the lee slopes of Chüpfenflue. This causes the formation of cornices at the ridges and some other interesting deposition patterns.

We use the meteorological observations of WAN3 as input for Alpine3D. Precipitation measurements used in this test were from the Weissfluhjoch Versuchsfeld (WFJ), as within our catchment we only have snow height measurements and can't separate drifting snow from precipitation. WFJ is a flat field station located 3 km NE of Wannengrat on a similar altitude (2544 m). A comparison of increases in snow water equivalent estimated from snow height changes at WAN3 with the measurements at WFJ showed that precipitation at WFJ is slightly larger. The effect on our study however, is very small as we will use the same input data for all simulations.

4. TEST CASE

As a test case for the drifting snow sublimation effects, we chose a period of 43 hours in March 2010. Most relevant meteorological observations at WAN3 are shown in Figure 2. Though wind speeds might seem too weak most of the time to cause drifting snow, one has to realize that at the ridges, the wind is much stronger.

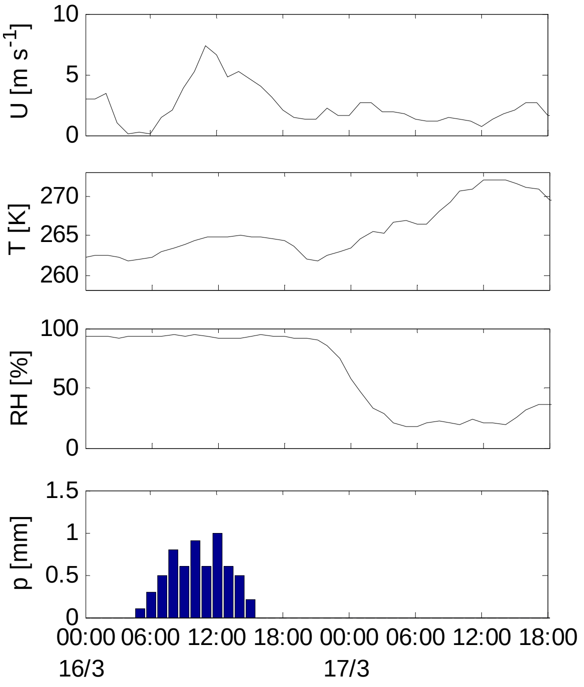

Figure 2 Hourly averaged wind speed [m s^{-1}], air temperature [K] and relative humidity [%] as observed during our test case at WAN3. Hourly precipitation [mm] in the same period observed at WFJ.

A period with moderate snowfall and NW wind was followed by a warm and dry period with weaker winds from the south. For this period, we want to simulate the snow distribution with Alpine3D, quantifying the influence of drifting snow sublimation by a comparison with different simulations in- or excluding sublimation and its feed-backs. We will use a horizontal resolution of 10 m for these simulations.

5. RESULTS AND DISCUSSION

To give some insight in the erosion and deposition pattern at Wannengrat, we show the change in snow water equivalent between the start and end of a simulation without drifting snow sublimation in Figure 3. Red colours indicate erosion, blue deposition. The northwest storm with precipitation causes a large accumulation in the lee slopes and the formation of cornices. In the period thereafter, with mostly winds from the south, there is some transport of snow from the cornice between Strela and Chüpfenflue to the north. However, the dominant snow distribution pattern is clearly caused by winds from the northwest. This is consistent with snow height measurements from Schirmer et al. (submitted, 2010).

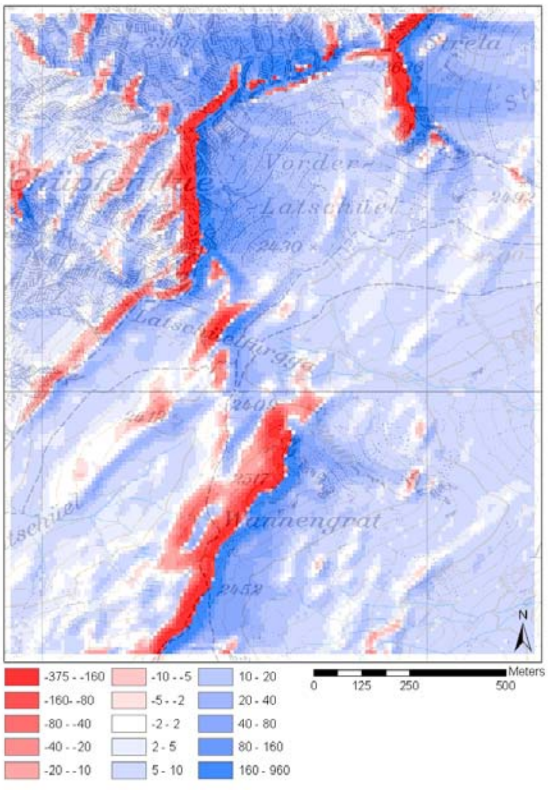

Figure 3 The modelled change in snow amount (mm w.e.) over a simulation period of 43 hours.

As a comparison, we run 3 simulations. In one we didn't include drifting snow sublimation, in the second simulation we included sublimation, but didn't account for any feedbacks. In the last simulation, we included sublimation and its feedbacks on temperature, humidity and concentration. We show results of the 3 simulations for a single point (indicated with a red + in Figure 1) in Figure 4.

During the first 23 steps, there is no difference in deposition at this location between the three simulations. In this period, the air is saturated and drifting snow sublimation has no influence on deposition. Once the relative humidity decreases however, we start to see differences.

In the upper graph, we see that a large amount of snow is deposited after 25 hours. At this time, there is a strong southern wind. Another peak in deposition is observed after 38 hours when there is a strong wind from the northwest. Drifting snow sublimation clearly reduces the deposition amounts during these warm and dry drifting snow events.

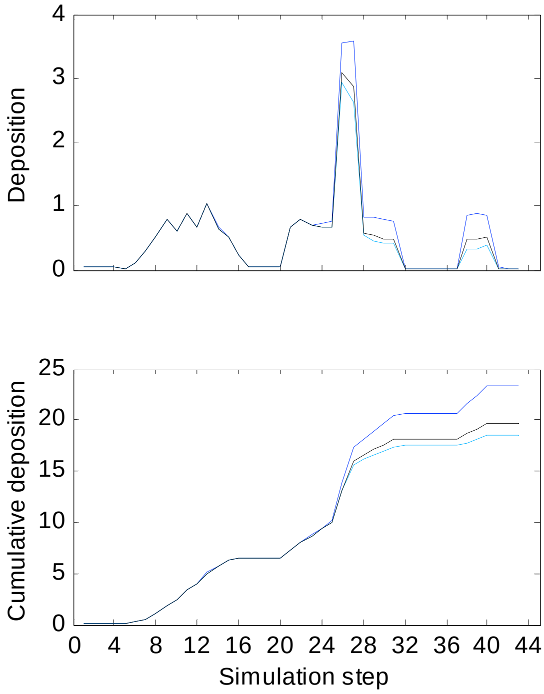

Figure 4 Modelled deposition [mm w.e.] and cumulative deposition [mm w.e.] during the test case at a point north of Chüpfenflue (indicated by a red + in Figure 1). Dark blue is a simulation without drifting snow sublimation. Light blue with sublimation but without feedbacks. Black a simulation including sublimation and feedbacks on T,q and c.

The original model estimates a total deposition of 23.4 mm w.e.. When introducing the sublimation, but excluding the feedbacks as many models do, the cumulative deposition after 43 hours is only 18.6 mm w.e., about 79 % of the original estimate. However, when we include the feedbacks as well, sublimation is less and deposition is 19.7 mm w.e., which is a significant difference to the simulation without feedbacks in only 43 hours. At this location, sublimation of drifting snow reduces the deposition over 43 hours by 15.8%.

There is a large spatial variability in drifting snow and therefore, we also need to look at the effects of sublimation at other locations within our catchment. Figure 5 shows the difference in the amount of snow (mm. w.e.) at the end of the simulation, between a simulation without sublimation and one with sublimation including all feedbacks. As during most of the warm and dry period the wind comes from the south, the largest effects are visible in the area where deposition is caused by southerly winds. Differences can be up to 20 mm w.e or 21 cm in snow depth (not shown). Though there are only 2 hours of NW wind in the dryer period, we still see a large difference in the amount of deposition (up to 10 mm w.e.) in the eastern lee slopes.

Furthermore we see that sublimation causes little reduction of deposition in the SE corner of the domain. In contrast to the large differences in other regions mentioned before, these are not specifically caused by drifting snow, as there is hardly any drifting snow here. These small differences evolved during snowfall.

Though local effects are important for snow cover stratigraphy, hydrologists might be more interested in average effects within a catchment. The spatially averaged accumulation (simulation without sublimation) was 16.6 mm w.e.. If we take the difference in final snow amounts between this simulation and a simulation including drifting snow sublimation and feedbacks, we see that we loose on average 0.52 mm w.e. over 43 hours. This is 3.1% of the average accumulation. Calculating the loss of deposition, but neglecting sublimation feedbacks gives an average loss of 0.73 mm w.e., this shows that feedbacks must be included in drifting snow sublimation calculations.

It would be very interesting to simulate the influence of sublimation during a winter season, as this would give a more general idea how important drifting snow sublimation is and would allow a better comparison to other studies.

However, as our model is computationally very intensive, these longer simulations are not available at the moment.

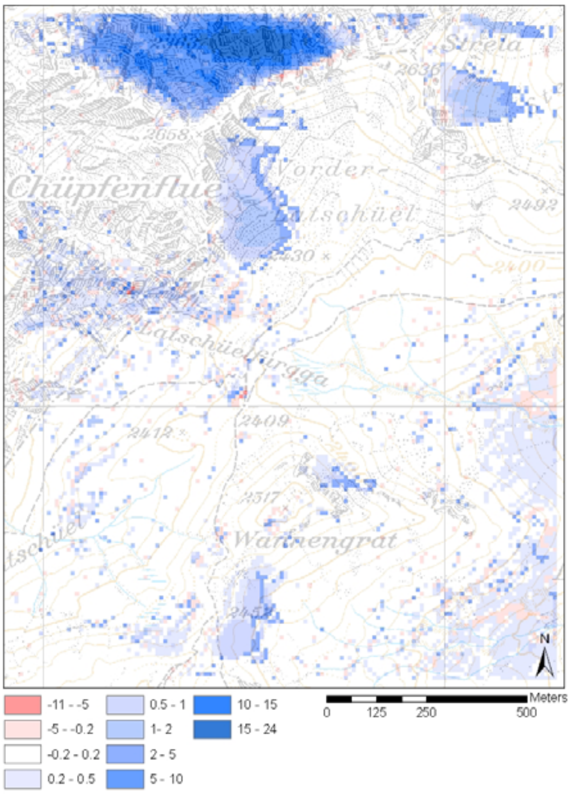

Figure 5 Difference in final snow amount (mm w.e.) between a simulation without and one with drifting snow sublimation.

Unfortunately, validation of the model is not possible since drifting snow sublimation has never been measured directly. The only possible way at the moment is indirectly by snow height measurements from a terrestrial laser scanner. Though these measurements have a high resolution and good accuracy, they are influenced by other processes such as snow settlement and surface sublimation and we would not be able to specifically assign the effects of sublimation. However, knowing that we use an adequate resolution, don't neglect important feedbacks on drifting snow sublimation and include the advection effects which cause saturation of the air further away from the ridge (not shown), we are confident that this model gives a more realistic estimate of drifting snow sublimation and its spatial variation than has been given so far for complex Alpine terrain.

CONCLUSION

By including a drifting snow sublimation routine in the existing snow transport model Alpine3D, we were able to show the importance of it in a complex Alpine catchment. Within a simulation of only 43 hours, the model overestimates the snow height by up to 21 cm if sublimation is neglected. Though the effects are local, they are significant, especially since they typically affect steep slopes where avalanche danger needs to be considered.

Furthermore, we showed that sublimation feedbacks on concentration, humidity and temperature need to be considered and that drifting snow sublimation reduces the accumulation within the simulation domain by 3%. This is consistent with a study by Strasser et al. (2008), who showed a similar loss of snow, but within a season. Showing how representative our study case is for a winter season in our catchment will be a next research step.

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