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SnowSlide: A simple routine for calculating gravitational snow transport

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[1] Knowledge about lateral snow transport processes is essential for the description of the spatial distribution of snow and therefore for the distribution of water on the lands surface. While numerous snow hydrological models are accounting for wind induced snow transport, they are mostly neglecting gravitational snow transport processes. This leads to unrealistic calculations of snow cover distributions in high Alpine regions effecting the subsequent prediction of individual components of the water and energy cycles at the land surface. "SnowSlide" as presented here is a fast and parsimonious model component allowing for the calculation of gravitational snow transport processes in an integral way. The functionality and performance of SnowSlide is demonstrated a) for artificial land surfaces and b) for two winter periods at the Watzmann massif in south-east Germany. It is shown that the integration of SnowSlide into the snow-hydrological model "SnowModel" is significantly improving the prediction of spatially distributed snow patterns in high Alpine areas and therefore generating more realistic descriptions of Alpine water and energy balances.

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1. Introduction

[2] Predicting water cycle dynamics of mountainous areas has long been recognized as an ultimate challenge in hydrological research [*Klemes*, 1990]. Limitations in the availability of measured data covering spatio-temporal variability of relevant processes has lead to deficits in an appropriate process understanding at different spatial scales and make prediction in these harsh environments extremely uncertain [*Blöschl*, 1999; *Blöschl et al.*, 1991a; *Klemes*, 1990]. In particular it is the spatial and temporal distribution of snow cover relevant to water resources management and to the energy balance in Alpine areas that is difficult to describe [*Blöschl et al.*, 1991b; *Liston and Sturm*, 1998; *Strasser et al.*, 2008; *Winstral and Marks*, 2002]. One of the most obvious observation, either via remote sensing or even by eye, is that the summit regions of high mountains even though receiving highest snow precipitation amounts are often snow free (Figure 1b). The responsible processes are in principal well known: (1) Preferential snow deposition as discussed, e.g., by *Lehning et al.* [2008] accounting for the interaction between wind and topography and leading to irregularly distributed snowy precipitation due to local and regional eddies; (2) snow transport by gravitative forces in form of singular events like avalanches or in form of snow slides [*Gruber*, 2007; *Sovilla et al.*, 2006; *Sovilla et al.*, 2007]; (3) wind induced snow transport modifying the original snow distribution especially under frequent high wind speed conditions also leading to large losses due to sublimation of snow in turbulent suspension [*Bernhardt et al.*, 2009; *Doorschot et al.*, 2001; *Lehning et al.*, 2006; *Liston and Sturm*, 1998; *Pomeroy and Gray*, 1990; *Pomeroy et al.*, 2006].

[3] While preferential snow distribution and wind induced snow transport are already implemented into current generation land surface models (LSM) [*Lehning et al.*, 2006; *Liston and Elder*, 2006; *Pomeroy and Li*, 2000] there are no LSMs known to the authors accounting for gravitational snow transport at least in a parsimonious way. Gravitational snow transport is especially effective in regions with steep terrain. The process leads to a displacement of snow from regions of higher to regions of lower elevations and is responsible for extreme snow depths e.g. at the base of steep slopes. These extreme snow depths are needed to adequately explain the existence of some small glaciers at such locations [*Kuhn et al.*, 1999]. Also, the transport of snow into lower regions leads to a modified runoff behaviour of the alpine catchment and to significantly modified melt patterns [*Strasser et al.*, 2008]. Hence, not considering this process will lead to noticeable bias in the prediction of glacier mass balances and in the calculation of the runoff generation of alpine catchments. A former and analogue approach of *Gruber* [2007] has shown good results in the Swiss Alps but was not tested within a land surface model accounting for a continuous snow cover development calculation as well as wind induced snow transport. We here address this lack by including an effective parsimonious process description ("SnowSlide") for horizontal snow transport, into an established physically based snow model ("SnowModel") [*Liston and Elder*, 2006] and show its performance at a synthetic topography and at the Watzmann massif (Figure 1). The model setup of SnowSlide allows for a fast transfer and application of the model to other sites by adapting just one model parameter.

2. Study Location

[4] Berchtesgaden National Park is a mountainous area reaching from about 600 m a.s.l. to 2713 m a.s.l. It is located at the south eastern part of Germany (12.4647 lat. and 47.5736 long.) (Figure 1). Model development was done at the Watzmann massif and at Watzmann east face (Figure 1, area b) which has a vertical height of about 1800 meters. We used a 30m DEM as model input. The minimum slope angle of the face is 0° the maximum angle is 84°. The surface is

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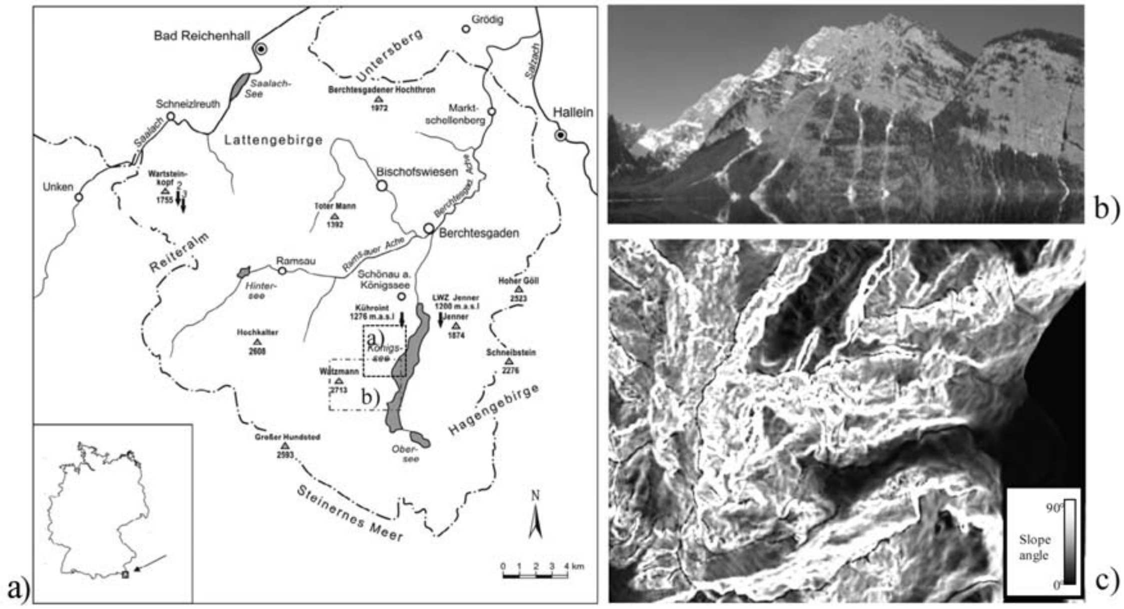

Figure 1. (a) General location of the test side, (b) an overview over the location in June 2005 (Figure 1a, area a), and (c) the slope angles at Watzmann east face (Figure 1a, area b).

solid rock. A detailed description of the test-site is given by *Bernhardt et al.* [2009].

3. Methods

[5] SnowSlide has been developed as a topographic driven model for simulating the integral effects of gravitational snow transport. It can be easily integrated into regularly gridded models and allows for the lateral transport of snow between grid elements. In contrast to models capable of describing the physics of avalanches like RAMMS [*Janetti et al.*, 2008], SnowSlide does not allow for the location of weak zones, the exact timing of snow slides and does not separate between starting, track and run out zone. SnowSlide is working in a continuous mode and is executed at any time step of the hosting model if a defined snow holding depth (S_{hd}) and a minimum slope angle (S_m) are exceeded. Based on manual calibration Sm was set to 25° here and is constant for all grid elements. The value of S_{hd} either depends on a vegetation dependent snow holding depth as defined by *Liston and Sturm* [1998] or is calculated over a regression function (Figure 2b). For the presented example the regression function is based on the assumption that the snow holding depth is high in flat regions and decreases exponentially with an increasing slope angle. The minimum value of S_{hd} was fixed to 5 cm snow water equivalent (SWE) and set constant from 75° on. This was done on the basis of a model calibration with respect to classified Landsat ETM+ data. The regression function and minimum S_{hd} treated constant here in this application may be unique for each location and can be calibrated on the basis of remotely sensed or field campaign data. If the snow holding depth defined according to *Liston and Sturm* [1998] and the ones as defined by the regression function differ, S_{hd} is set to the higher of the two values, independent of the existence of vegetation.

[6] SnowSlide uses an internal loop structure. Rather than operating a sequential grid order, SnowSlide starts at the

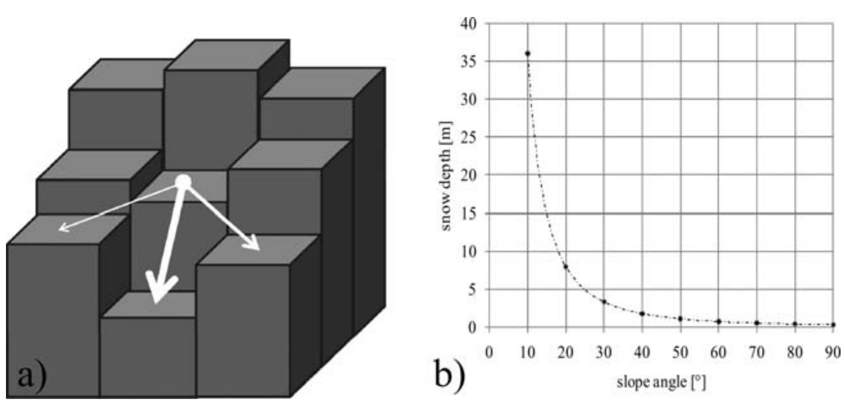

Figure 2. (a) Graphical illustration of the operational mode within SnowSlide. Different transport rates to lower adjacent pixel are indicated by the thickness of the white arrows. (b) Definition of the snow holding depth dependent on the slope angle by an exponential regression function.

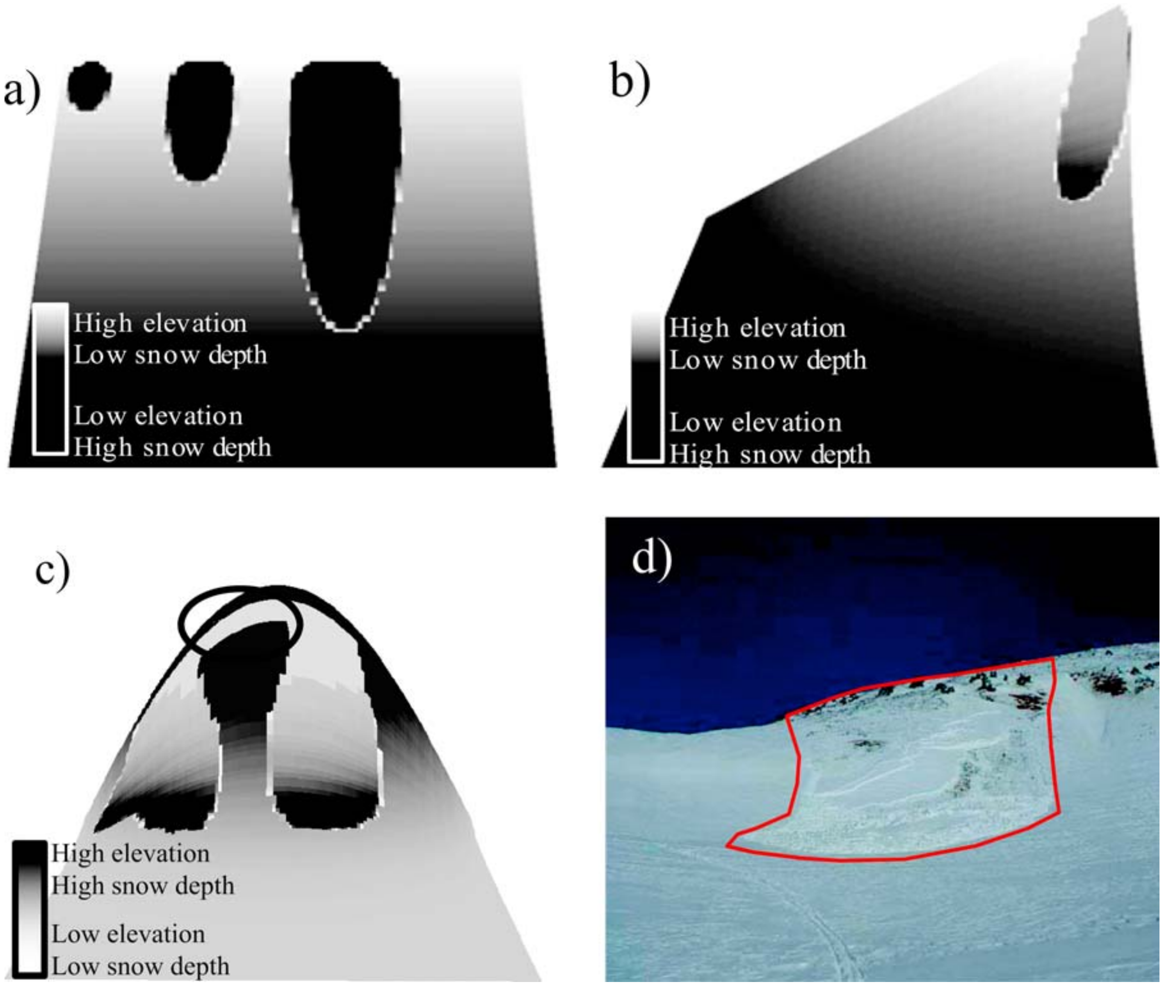

Figure 3. Results of SnowSlide runs using (a) a sloped surface and 3 snow packages with a different size, (b) a surface with an exponential sloped surface, and (c) an exponentially sloped surface with a wall (encircled area). (d) A real slab avalanche a surface.

highest and ends at the lowest elevated grid element thus avoiding snow transport into already processed grids. In a first processing stage it is tested whether the slope angle of a grid element exceeds S_m and whether the current snow depth given by the hosting LSM exceeds S_{hd}. If true, the surrounding grid elements are scanned and the number of elements located below the initial element is determined (Figure 2a).

[7] SnowSlide does not use the original DEM for this test, but rather operates on the current snow DEM (snow depth plus surface elevation). Snow available for transport corresponds to the difference between the grid cells snow holding depth and the current snow depth. It is transferred to the lower neighbours and is portioned based on the vertical distance between neighbouring and initial grid elements. The presented scheme allows for divergent and convergent flow and is strictly mass conserving. SnowSlide was used as standalone routine and in combination with the well established snow model SnowModel [*Liston and Elder*, 2006].

4. Results

[8] Initially, standalone runs were realized on synthetic surfaces for verifying the general model performance. First, a sloped surface (Figure 3a) with a constant slope angle of 80° was used. S_{hd} was defined over the regression function shown in Figure 2b, and 8, 24 and 92 grid elements were filled with an initial snow depth of 20m per grid element (from left to right in Figure 3a). As the slope angle is constant, S_{hd} is also constant (Figure 2b). This leads to a run out length which is exclusively driven by the initial snow depth. Furthermore, the snow depth within the snow slide is uniform and identical to S_{hd} in this case. If an exponentially slope profile is used (Figure 3b), both the run out length and the snow depth within the snow slide are showing a dependency on the altering S_{hd} value. As a third example, an idealized wall structure was included into the DEM for generating a divergent flow; the initial snow pack was located behind the wall (53 pixels in length and 20m snow depth). If SnowSlide is executed some snow is accumulated directly behind of the wall (encircled area in Figure 3c) the remaining part is sliding downwards with respect to topography and S_{hd}. These results are well in line with expectations and are very similar to the snow distribution within a slab avalanche shown in Figure 3d.

[9] In a next step SnowModel [*Liston and Elder*, 2006] with and without SnowSlide was executed at Watzmann massif (Figure 1) using a 30m DEM and hourly data of six

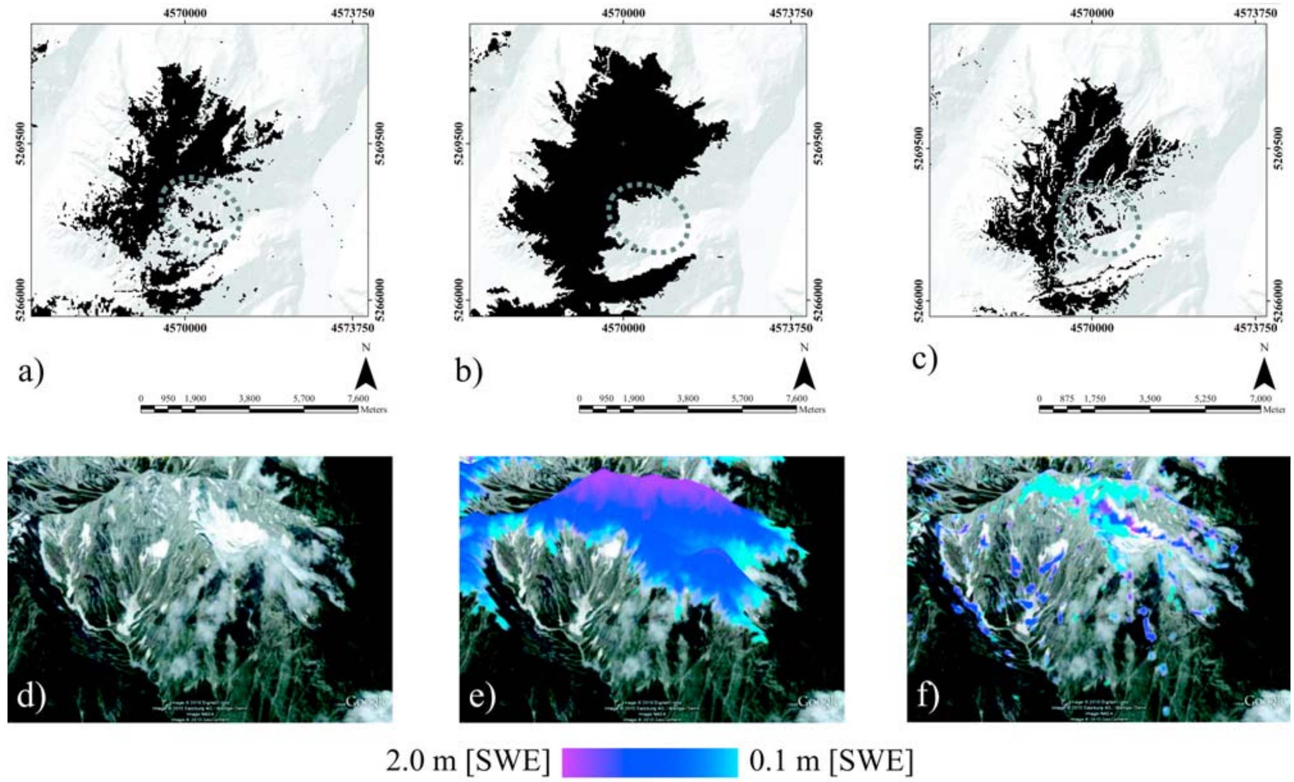

Figure 4. (a) The extent of the classified snow cover (30 May 2004) is shown in black based on Landsat ETM+ image, (b) model result of SnowModel [*Liston and Elder*, 2006] for the same date and without lateral snow transport processes, and (c) SnowModel result including SnowSlide, (d) the snow distribution at Watzmann at 1 August 2005, the crest region is roughly snow free while the rock shoulders and avalanche paths are still snow covered, (e) result of SnowModel without lateral snow transport: the snow distribution is controlled by the precipitation and temperature distribution within the area, (f) SnowModel predictions including SnowSlide leading to a heavily modified snow distribution. All of the model results are displayed in Google Earth.

meteorological stations. A detailed description of the hosting SnowModel, data used, the model set up and a case study for the test site is given by *Bernhardt et al.* [2010]. The calculated snow cover development of the winter season (September–August) 2004/05 and 2005/06 was spatially compared to the snow covered area defined over classified Landsat ETM+ images. For the estimation of the snow covered area in May 2004, the normalized difference snow index (NDSI) was used. The NDSI trace back to band rationing techniques [*Dozier*, 1984] and is related to the NDVI [*Tucker*, 1979] (Figure 4a). For August 2005 an aerial image (Google Earth) was used for comparison.

[10] The visual comparison of Figures 4a–4c reveals that SnowModel results (Figure 4b) are too homogenous in comparison to the Landsat classification (Figure 4a) when lateral transport processes are neglected. The inclusion of SnowSlide on the other hand leads to a more satisfying convergence between model result and classification (Figures 4a and 4c). This is especially true for the east face of the mountain where significant snow volumes are transported downwards and are accumulated in singular firn fields (Figures 4a and 4c).

[11] For a more quantitative evaluation and comparison of different model performances two different measures for the goodness-of-fit ($F^{<1>}$ and $F^{<2>}$) based on a binary contin-

Contingency Table	Observed Snow	Observed No Snow
Modelled		
Snow	a (hits)	b (fails)
No snow	c (misses)	d (zero)

$$F^{<1>} = \frac{\sum_{i=1}^{n} a + \sum_{i=1}^{n} d}{n} \qquad (1)$$

$$F^{<2>} = \frac{\sum_{i=1}^{n} a}{\left(\sum_{i=1}^{n} a + \sum_{i=1}^{n} b + \sum_{i=1}^{n} c\right)} \qquad (2)$$

	SnowModel Without SnowSlide	SnowModel With SnowSlide
$F^{<1>}$	0.81	0.89
$F^{<2>}$	0.64	0.67

Figure 5. Definition of performance measures according to *Aronica et al.* [2002] and results for the May 2004 snow distribution modelling with in without the integration of SnowSlide into SnowModel.

gency table of observed snow covered and non snow covered grid elements according to *Aronica et al.* [2002] were applied (Figure 5). The consideration of horizontal snow transport by integrating SnowSlide into SnowModel leads to a significant improvement of the model results with respect to both performance indices (0.81 vs. 0.89 for $F^{<1>}$ and 0.64 vs. 0.67 for $F^{<2>}$).

[12] Figure 4d shows the Watzmann massif at a later date at 1 August 2005, including the permanent firn field "Ice Chapel" at the base of the east face [*Rödder et al.,* 2010]. SnowModel results with and without lateral transport are displayed in Figures 4e and 4f, respectively. It is obvious that the modelled snow depth shown in Figure 4e, that can be seen as representative for most of the current generation snow and hydrological models, is nearly exclusively controlled by elevation when neglecting lateral snow transport. The increase of the snow depth with elevation is due to higher amounts of snowy precipitation and lower temperatures at higher elevations.

[13] However, these results do not properly reflect the snow distribution under real conditions (Figure 4d, also Figure 4a) as resulting from preferential deposition, wind induced and gravitational snow transport. These processes modify the initial snow distribution either during the snow fall event itself or during successive time periods, thereby massively reducing deep snow packs at the crest regions. While SnowSlide does not explicitly describe all of the gravitational transport terms on a small scale physical base (see section 3), it well represents the integral effects of gravitational snow redistribution on larger scales as can be observed e.g. at the Watzmann east face (Figures 4d–4f). A similar snow distribution pattern could not be reproduced by just simulating wind induced snow transport processes when using SnowModel with downscaled 30m resolution MM5 wind fields [*Bernhardt et al.* 2010].

5. Discussion

[14] There exists a large variety of different complex stand alone snow models and snow model components within LSMs ranging from relative simple temperature index models [e.g., *Hock*, 2003], to complex physically based models [e.g., *Lehning and Fierz*, 2008]. As illustrated in the previous section, these models will reach their limitations within rough or high mountain terrain when neglecting lateral transport processes (Figure 4). We here presented a relatively simple and effective approach, SnowSlide, to consider lateral snow transport processes within regularly gridded models. Model runs on synthetic surfaces have initially shown that realistic slide formations can be produced (Figure 3), however, these test have to be extended to more sophisticated and physically based approaches like e.g. RAMMS [*Janetti et al.*, 2008]. The results under real conditions that have been achieved for the Watzmann Mountain show that the SnowSlide approach is a good approximation of the complex horizontal snow transport processes. Its integration into a current generation snow-hydrological model significantly improves the representation and prediction of observed snow distribution pattern (Figure 4). We are convinced that this procedure allows for improved assessment of the impact of heterogeneous snow cover on the energy and moisture fluxes, the runoff generation and the retreat of glaciers in alpine regions within e.g. Global Change scenarios, which is a topic under current investigation that is presented in the near future.

[15] The model is written in FORTRAN and is made available from the authors.

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