Simulation of seasonal snow-cover distribution for glacierized sites on Sonnblick, Austria, with the Alpine3D model

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ABSTRACT. A detailed model of Alpine surface processes is used to simulate the amount of preferential deposition as well as redistribution of snow due to snowdrift for two alpine glaciers (Goldbergkees and Kleinfleißkees, Austrian Alps). The sequence of snow-cover modelling consists of the simulation of the wind field with a mesoscale atmospheric model, a three-dimensional finite-element drift module, an energy-balance module and a snowpack module. All modules with the exception of the wind-field model are integrated within the Alpine3D model frame. The drift module of Alpine3D distinguishes between saltation and suspension and is able to capture preferential deposition of snow precipitation and redistribution of previously deposited snow. Validation of the simulated snow depth is done using the spatially dense snow-probing dataset collected during a campaign in May 2003. Simulated snow depths agree with measurements during winter 2002/03 at locations with detailed snow-height monitoring, taking into account the high spatial variability of snow depth on the glacier. Moreover, comparison of snow accumulation from model results with detailed probing on 1 May 2003 for the total glacier area shows that Alpine3D is able to capture major patterns of spatial distribution of snow accumulation. For the first time, the Alpine3D approach of using high-resolution wind fields from a meteorological model and a physical description of snow transport could be validated for a very steep glacierized area and for a full accumulation season. The results show that drift is a dominant factor to be considered for detailed glacier mass balances. Another dominant factor not considered in this study may be snow redistribution due to avalanches.

INTRODUCTION

The investigation of the spatial variability of snow depth in high alpine areas is an important topic in snow hydrology and glacier research (Takahashi and others, 1988; Pomeroy and others, 1997; Déry and others, 1998; Essery and others, 1999; Lehning and others, 2006; Liston and others, 2007). So far, however, most studies either assume that the snow cover is only dependent on snow precipitation and do not account for the influence of wind on snow distribution or use simple statistical approaches to consider wind effects.

In a highly structured alpine terrain, the snow accumulation is highly dependent on orography during the winter. The dependence is not only on elevation, aspect and slope at the point of interest but also on all features in the surroundings which influence the near-surface wind field. The locally convergent and divergent flow patterns cause snow redistribution. Not only is previously deposited snow influenced, but also snow precipitation is non-uniformly deposited because of the wind (Lehning and others, in press). The orography also leads to a highly varying surface energy balance.

It was shown in the work of Hartman and others (1999) that detailed information about the spatial distribution of snow water equivalent is necessary for runoff modelling in glacierized catchment areas. Similarly, Michlmayer and others (in press) concluded that the investigation of the snow height distribution for the glacierized catchment area of Goldbergkees is essential for investigating hydrological budgets. Since the drift is dependent on snow type, the temporal development of the distributed snow cover also needs to be considered (Lehning and others, in press).

This study aims to investigate seasonal accumulation and erosion patterns due to snowdrift and preferential deposition for two glaciers (Kleinfleißkees and Goldbergkees) located at Sonnblick mountain in the Austrian Alps (Auer and others, 2002) (Fig. 1). The study region is climatologically characterized by strong gradients of the precipitation field from inner-alpine dry valleys to a high-level precipitation region on the north-facing slope of the Alps. The Sonnblick area is outstanding with respect to the dense network of hydrological, glaciological and meteorological measurements. Results from this investigation will not only improve the understanding of high-Alpine snow distribution and snow-cover development but will also provide more insight into the relation between snow precipitation and deposited snow at high-elevation sites.

STUDY AREA AND OBSERVATIONAL NETWORK

The Sonnblick area is located in the Hohe Tauern region, part of the central Austrian Alps. The two glacier basins cover an area of 1.49 km^2 (Goldbergkees) and 0.95 km^2 (Kleinfleißkees). The altitude range of the test site is 750 m.

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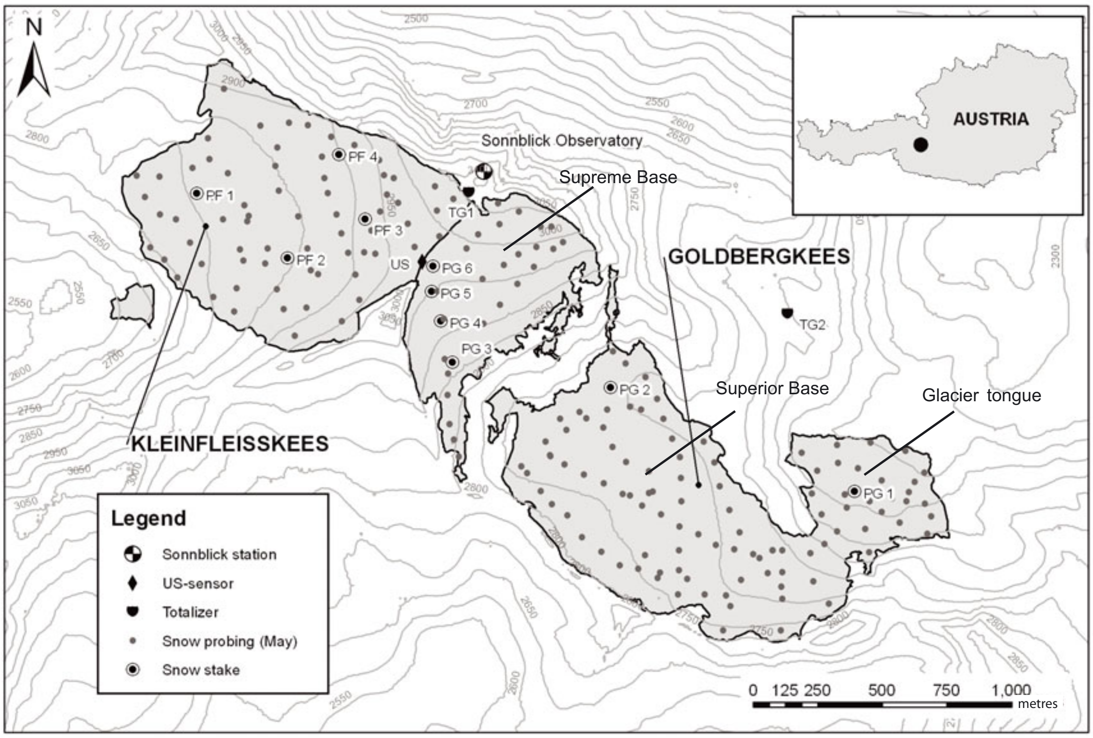

Fig. 1. Research area of Goldbergkees and Kleinfleißkees.

The highest point is Sonnblick summit at 3105 m a.s.l. The surrounding topography of the glaciers is characterized by steep alpine terrain with slopes of up to 60° north of Sonnblick summit.

All meteorological data used to run the Alpine3D model were collected from the Sonnblick observatory and its weather station, located at the top of Sonnblick. The Sonnblick area provides a dense observational network (Fig. 1). In Figure 1, the locations of precipitation measurements (totalizer), monthly snow-stake readings (snow stakes), seasonal snow probing and the ultrasonic sensor for daily snow-depth measurements are shown. The mass-balance for the accumulation period is determined each year at the end of the accumulation season by probing the snow cover (depth measurements) and executing density measurements. From these measurements, a spatial distribution of the snow depths was obtained by interpolating the measured values.

MODEL MODULES

Using model simulations to distinguish between accumulation and erosion areas at the glacier basin requires a detailed description of snow-surface processes and therefore snow-cover development. The modular and spatially distributed modelling approach of the physically based model Alpine3D is specifically tailored to this application. The mesoscale atmospheric model Advanced Regional Prediction System (ARPS) has been used for the reproduction of small-scale flow fields (Raderschall and others, in press) for input to the drift module (Lehning and others, in press).

Small-scale flow simulation

High-resolution wind fields over the complex topography of the Sonnblick area were computed with the mesoscale atmospheric model ARPS. ARPS is an atmospheric prediction model which solves the non-hydrostatic and compressible Navier–Stokes equation on a staggered Arakawa C-grid. The model has been developed at the Center for Analysis and Prediction of Storms (CAPS), University of Oklahoma, USA (Xue and others, 2000, 2001). A more detailed discussion of the model can be found in Raderschall and others (in press).

The main goal of the flow simulation in the context of our study was to reproduce dynamically induced flow features in the mountainous target area. The drift model only uses the characteristics of the mean flow as influenced by the complex topography. This includes terrain-induced vertical velocities and zones of flow convergence or separation.

Alpine3D model

For the modelling of the seasonal snow-cover development and snow-cover distribution, the physically based model Alpine3D was used. The general aim of the model is to simulate alpine surface processes and their spatial and temporal variability. In the current study the snow-transport module, the radiation energy-balance module and the snowpack module (SNOWPACK) were used. Further information on the models and the coupling strategy of the Alpine3D model are given by Lehning and others (2006, in press).

The three-dimensional (3-D) snow-transport module includes the processes of saltation, suspension and erosion/deposition. The saltation process is described by the equilibrium saltation model of Clifton and Lehning (in press). The formulation for determining the steady-state mass flux of saltation is also valid for slopes. The suspension is described by a stationary equation, which is solved with a stabilized finite-element method. The model is therefore able to capture

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preferential deposition of snow precipitation and to compute the erosion and transport of previously deposited snow. The feedback of drifting snow on the flow field and sublimation of snow are neglected. The turbulence is parameterized from similarity theory. A detailed description of the snow-transport model is given in Lehning and others (in press).

To predict snow-cover characteristics and the erodibility of snow, the finite-element based physical snow-cover model SNOWPACK is used and equations for instationary heat transfer and settlement in a phase-changing snow cover are solved. Furthermore, the formation of surface hoar and snow metamorphism is included by describing the microstructure in terms of grain form, grain size, dendricity and sphericity. A full description of SNOWPACK can be found in Bartelt and Lehning (2002) and Lehning and others (2002a,b).

The 3-D radiation energy-balance module is based on a view-factor approach. In complex terrain, the topographic effects resulting from varying inclination and exposition strongly influence the radiation balance. Shortwave reflections and longwave emissions from terrain are therefore taken into account.

Simulation settings

The snow-cover development and snow-cover distribution at the glacierized sites, Goldbergkees and Kleinfleißkees, was simulated for the 2002/03 accumulation season. The simulation with the Alpine3D model began on 1 October 2002, the approximate date of the end of the previous ablation season, and ended on 1 May 2003, the approximate date when maximum accumulation of snow is expected. The grid for modelling the snow-cover development and snowdrift covers an area of $4.5 \times 2.6\,km^2$. The flow simulation with the ARPS model was performed for a larger grid extent of $8.6 \times 5.4\,km^2$, in order to limit the effect of the domain boundary. The horizontal resolution for the ARPS and Alpine3D grids is 25 m. As a consequence of grid stretching, the vertical resolution varies from 3 m at the near-surface layers to 50 m at the upper levels. A domain height of approximately 3000 m above the topography was chosen.

A statistical classification of the near-surface wind field for most frequent wind directions was carried out based on the wind measurements at the meteorological station at Sonnblick. In order to use computer time efficiently, this classification schema was used to reduce the flow simulations with the ARPS model to the most frequent flow directions, measured at the reference station at the Sonnblick summit.

The flow model was initialized with different atmospheric profiles such that the major wind directions chosen and the corresponding wind speeds at the reference station at the Sonnblick summit could be reproduced. The wind was initialized applying a standard logarithmic wind profile for the boundary layer. The boundary-layer height was set to 500 m. An aerodynamic roughness length of 0.01 m for a snow-covered topography was chosen (Raderschall and others, in press). The vertical profiles of the atmosphere were assumed to be slightly stably stratified and humid. The model run begins with horizontally homogeneous initial fields. The flow fields were calculated until the flow approaches a steady state. This quasi-stationarity of the flow field could be reached after ~240–260 s integration time. The assumption of a more stable stratification of the atmosphere leads to a shorter integration time for a stable adaption of the wind field to the topography (Raderschall and others, in press).

For the upper boundary condition, the zero-gradient formulation was applied. The bottom boundary condition was taken as a rigid wall, and for the lateral boundaries periodic boundary conditions were used. The flow fields were the hourly input for the drift simulations which were run for the whole accumulation season. The time-step for calculating drift, radiation energy balance and snow-cover status was set to 1 hour. To initialize the snow-cover status at the start of the simulation with the Alpine3D model, a land-cover classification was carried out by mapping the snow and ice distribution onto the two glaciers on 1 October 2002. Four initial land-cover classes were introduced: rock, bare ice, firn and old snow. All meteorological parameters were used as an hourly input for the Alpine3D model.

The meteorological parameters such as precipitation rates, air temperature, global radiation and relative humidity not taken from ARPS were obtained from measurements at the Sonnblick observatory. The measured precipitation rates, which were obtained from the totalizer TG1 near the Sonnblick observatory (Fig. 1), prescribed the lateral and the upper boundary condition for the suspension model. An altitudinal lapse rate was applied for the air temperature and the relative humidity was assumed to be uniformly distributed over the study area. The global radiation was redistributed by the energy-balance module. The ARPS mesh was used to define the finite elements within Alpine3D.

RESULTS

Preferential deposition and snow transport as influenced by the flow field

Preferential deposition is the heterogeneous deposition of snow precipitation over complex terrain in the absence of local erosion and saltation (Lehning and others, in press). Snow is non-uniformly deposited as a consequence of different flow features, caused by the complex topography. The main flow features influencing preferential deposition are the speed-up effects at mountain ridges, flow seperation and down- and updraft zones. Preferential deposition takes place even if the wind velocities are too small to exceed the threshold of saltation initiation. With increasing wind velocities, snow-transport processes become stronger as a result of the onset of saltation.

First, we simulated drift periods during an artificial snowfall event in order to find potential accumulation areas. For this purpose, different drift periods were modelled for 24 simulation steps (24 hours) and a constant precipitation rate of $1\,mm\,h^{-1}$. This precipitation is spatially distributed by preferential deposition forced by the suspension model.

Figure 2 presents the results of one drift period with wind velocities high enough to initiate saltation during a snowfall event. In Figure 2a–c the resulting snow-depth distribution as a consequence of the modelled stationary flow field is shown. The Alpine3D model was initialized for 24 time-steps with the same steady-state wind field with the main wind direction from southwest.

In Figure 2a, the general pattern of the erosion in the wind-exposed sites of the ridges and the deposition in the lee slopes of the southern ridge can be seen. The accumulation and erosion patterns are strongly influenced by the varying wind speed, shown in Figure 2b. Erosion patterns correspond to that of strong wind velocity. Note that the maximum velocity at the first gridpoint above the ground is reached at the southern ridge, due to speed-up effects. The minima in

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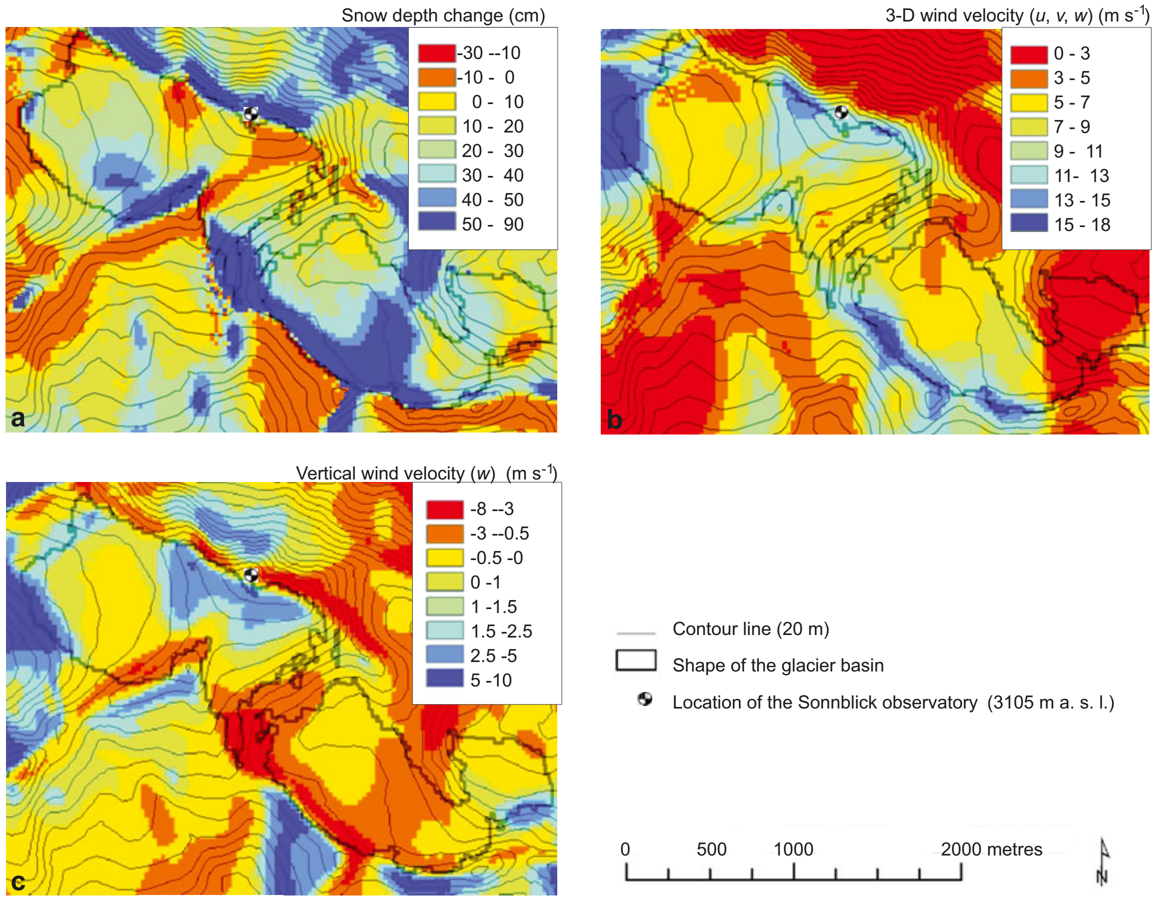

Fig. 2. Potential snow accumulation after 24 hours as a result of spatially variable deposition and snow redistribution during southwesterly wind conditions. All wind-related quantities are for near-surface gridpoints of the related steady-state wind field: (a) snow-depth change (cm); (b) wind speed; and (c) vertical component of wind velocity w (m s^{-1}).

wind velocity are at the central parts of the glaciers (Fig. 2b). Accumulation and erosion of snow is dominated by the angle between the mean wind vector and the topography surface, which leads to a mean vertical wind w close to the ground (Fig. 2c). Erosion or non-deposition generally occurs in front of mountain ridges. Accumulation occurs in the lee slope of a ridge. Lehning and others (in press) show that the ridge-scale snow distribution is mainly dominated by the vertical component of the wind velocity field.

Seasonal snow-cover distribution

The snow-cover development at Goldbergkees and Kleinfleißkees covering the entire 2002/03 accumulation period was simulated with the Alpine3D model initialized by the ARPS flow fields. Note that the spatial resolution of 25 m is not sufficient to simulate small-scale erosion and deposition patterns. In Figure 3, the snow-depth distribution is presented for the glacierized areas Goldbergkees and Kleinfleißkees for 1 May 2003. For the interpolation of the measured snow depths, a spline method was used.

Although the model results show a higher variability and larger maxima of snow depths, Figure 3 indicates that accumulation patterns as affected by the flow fields and varying radiation conditions are captured by the Alpine3D model. Taking into account that snowdrift is a non-linear process, the overestimation of the accumulation and erosion processes is considered to be a result of the simplification of stationary flow and associated deposition for hourly time intervals. In Figure 3c, the relative deviation of modelled snow depths from the interpolated values of measurements is shown. The greatest differences between modelled and measured snow depths are found in areas of strong snow accumulation and intense snow erosion.

The largest values of snow accumulation have been computed for the areas in the lee of the southern ridge of both glaciers. In general, computed and measured patterns of maximum snow accumulation match. The best model results were computed for the Superior Base, which defines the central part of Goldbergkees. In addition, a local minimum of snow depth near the observatory at the Superior Base was modelled. This phenomenon can be attributed to flow deflection at the crest of Sonnblick mountain.

Due to high wind velocities, the erosion processes are partly overestimated by the drift module. Such an erosion zone is presented in the central part of the Supreme Base at Goldbergkees. Snow is transported either by wind or by avalanches. The redistribution of snow by avalanches is not considered in this study. This results in an underestimation of snow accumulation compared to measurements, particularly for regions where snow deposition by avalanches is high. From personal observations (R. Mott, 2008), avalanche deposits contribute to the snow distribution at the glacier tongue of Goldbergkees and at the Supreme Base and the Superior Base close to the southern ridge of Goldbergkees.

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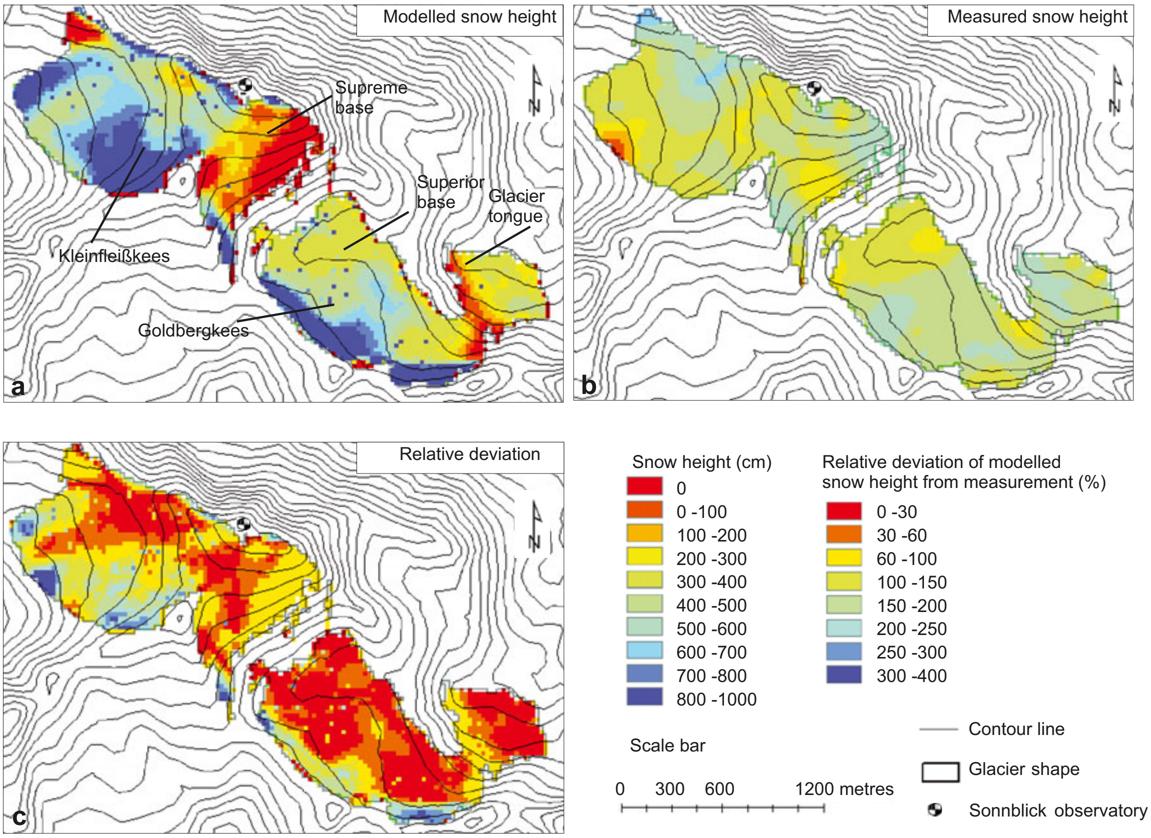

Fig. 3. Modelled and measured seasonal snow-depth distribution for the Goldbergkees and Kleinfleißkees region in 2003.

CONCLUSIONS

We have simulated snow distribution for a whole accumulation season over a glacierized area. We have demonstrated that snow-transport processes forced by simulated wind fields (described by a 3-D finite-element drift module), an energy-balance module and a snowpack model are important for the snow distribution.

The spatial pattern of erosion and accumulation was captured by the Alpine3D model for large parts of the glacier basins with good accuracy. A minor number of extreme pixels in the simulation domain showed a high overestimation of snow deposition or erosion. An extreme pixel is one which has a large upwards or downwards wind velocity in the ARPS simulation. At those pixels, which are typically close to a ridge, relative deviations between modelled and measured snow height can be up to 300%.

Although the current simulation setting is insufficient to present the small-scale variability of the snow cover, the model is considered to be a valuable tool within the scope of glacier mass-balance research. In particular, glacier hydrology studies require an accurate representation of the spatial variability of snow water equivalent and winter precipitation. Linking our model results to runoff modelling should therefore improve the runoff results based on the analysis of Michlmayer and others (in press) for the same area. Furthermore, snowdrift processes have a strong impact on snow-cover development in regions of strong accumulation and erosion. The important interactions between snow-cover development and drift processes are therefore considered in the physical model used for this study.

The snow-cover distribution on the glacierized sites is strongly dependent on the local wind fields. Because of the high computational time for wind-field simulations, a classification scheme has been applied. It is important to note that the drift is driven here by flow fields that represent only a modelled stationary mean wind, further simplified by the classification scheme. A future research area will be to determine how a more realistic time development of the flow fields and resolved turbulence will improve the simulation of snow distribution. Since snowdrift is a very non-linear and highly intermittent process, it is surprising that our simplified approach is able to predict a reasonable local snow mass balance over a full accumulation season.

A factor which is currently not included in Alpine3D, but thought to be important for the local mass balance especially of such small glaciers (Michlmayer and others, in press), is the lateral mass movements due to snow avalanches in the steep surrounding of the glacier basins. While our work suggests that drift is the dominant factor, additional work will be required to assess the relative importance of these two transport mechanisms.

Despite the high density of glaciological and meteorological measurements in our study area, even more measurements would be desirable for a more complete model validation. In particular, a fully 3-D measurement system of the wind field in such terrain is considered to be a major step for a deeper understanding of the flow–transport interaction. Additionally, remote-sensing techniques can help to obtain a higher-resolution picture of the true snow distribution.

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ungauged basins) and is partly funded by the Austrian Academy of Sciences. Part of the work is also supported by the Swiss National Science Foundation and the European Community. The wind simulations were made using the Advanced Regional Prediction System (ARPS) developed by the Center for Analysis and Prediction of Storms (CAPS), University of Oklahoma. We thank G. Koboltschnig, T. Egger, M. Schirmer, D. Binder and H. Holzmann for supporting the work in various ways. We also thank the anonymous reviewer who helped to improve the paper considerably.

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