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High resolution modelling of snow transport in complex terrain using simulated wind fields

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Abstract

Snow transport is one of the most dominant processes influencing the snow cover accumulation and ablation in high alpine mountain environments. Hence, the spatial and temporal variability of the snow cover is significantly modified with respective consequences on the total amount of water in the snow pack, on the temporal dynamics of the runoff and on the energy balance of the surface. For the presented study we used the snow transport model SnowTran-3D in combination with MM5 (Penn State University – National Center for Atmospheric Research MM5 model) generated wind fields. In a first step the MM5 wind fields were downscaled by using a semi-empirical approach which accounts for the elevation difference of model and real topography, as well as aspect, inclination and vegetation. The target resolution of 30 m corresponds to the resolution of the best available DEM and land cover map. For the numerical modelling, data of six automatic meteorological stations were used, comprising the winter season (September–August) of 2003/04 and 2004/05. In addition we had automatic snow depth measurements and periodic manual measurements of snow courses available for the validation of the results. In this paper we describe the downscaling of the wind fields and discuss the results of the snow transport simulations with respect to the measurements and remotely sensed data.

1 Introduction

In alpine terrain wind induced snow transport leads to a significant redistribution of the existing snow cover (Doesken and Judson, 1996; Pomeroy et al., 1998; Balk and Elder, 2000; Doorschot, 2002; Bowling et al., 2004; Bernhardt et al., 2008). As a result snow is transported from windward into lee regions, into sinks, and at the windward side of taller vegetation (Pomeroy et al., 1993; Liston and Sturm, 1998; Hiemstra et al., 2002). The resulting heterogeneity has effects on the energy balance, the total amount of snow water equivalent (SWE) and the timing and intensity of snowmelt runoff as well as the avalanche risk (Liston, 1995; Liston and Sturm, 1998; Liston et al., 2000; Lehning, 2006). Furthermore snow transport can lead to an increase of the sublimation rates of the snow cover itself and of airborne snow particles. For the prediction of these processes many models were developed over the last years (Liston and Sturm, 1998; Déry, 1999; Essery et al., 1999; Winstral and Marks, 2002; Lehning et al., 2006). Nevertheless, the appropriate reproduction of snow transport processes is not only dependent on the snow model used, but also on the representativeness of the meteorological information. In this context, very sensitive parameters are wind speed and direction (Essery, 2001; Lehning et al., 2000; Eidsvik et al., 2004; Bernhardt et al., 2005). Winstral and Marks (2002) outlined the difficulties of constraining this parameter in alpine terrain. Bernhardt et al. (2008) utilized a library of MM5 wind fields for providing physically derived wind fields as input for the snow transport model (Fig. 1). Former studies have demonstrated the general functionality of the approach at a relatively coarse scale (200 m) (Bernhardt et al., 2008). In general, it can be stated that modelled snow transport activities increase under usage of MM5 wind fields in comparison to the usage of interpolated wind fields. Furthermore, erosion is much more intensive at windward location as ablation processes are dominant at the leeward sites of the ridges. This is in line with the expectations (Barry, 1992) but was not fulfilled when using interpolated wind fields (Bernhardt et al., 2008). Unfortunately the precise spatial location of accumulation and erosion zones was impossible at the 200 m scale (Bernhardt et al., 2008). For determining these locations, model-runs, with higher spatial resolutions are necessary. SnowTran-3D and all other components of the snow model package are completely scale independent which permits model-runs up to a resolution of 5 m (Liston and Elder, 2006). For the presented study a target resolution of 30 m will be used which corresponds with the GIS data (vegetation and DEM) and is sufficient for the comparison to field campaign data. Therefore, the MM5 wind fields had to be downscaled. The whole downscaling procedure is described in the following sections. The accuracy of snow model results produced with interpolated station measurements and with the downscaled wind field library was validated with remotely sensed data of the winter season 2003/2004 and field campaign data of the winter season 2004/2005.

2 Study area

The "Berchtesgaden National Park" is located in the southeast of Germany within the Free State of Bavaria (Fig. 2). The park is centered near 47°36′ N, 12°57′ E and covers an area of 208 km^2 with an average altitude of approximately 1000 m a.s.l. The high alpine area is characterised by rapid changes in elevation (minimum altitude: 501 m a.sl., maximum altitude 2713 m a.s.l.). The difference between the "Königssee" (sea level 603 m a.s.l.) and "Watzmann" summit (2713 m a.s.l.) is about 2100 m with a horizontal distance of only 3.5 km.

The climate of the National Park area is subject to significant spatial variability, strongly influenced by topography. Small scale local differences are caused by the general position in the mountainous landscape, the windward or lee position to the prevailing winds, and solar incidence angles.

Due to its status as a biosphere reservation, we can assume undisturbed testing conditions and human influences can be neglected. The described study investigates the winter season of 2004/2005; meteorological data for this period were available from six automatic weather stations (Table 1). Snow depth measurements were provided by a field campaign (Figs. 3 and 4).

GIS information of vegetation and topography were provided by the National Park authority. The vegetation dataset is based on an interpretation of colour infrared aerial photographs (personal communication of Helmut Franz). The used DEM was derived from 20 m contour lines. Both data sets provide a spatial resolution of 10m and were resampled to 30 m.

For the described study we applied our model on two sites: Kühroint and Reiteralm (hatched areas).

Kühroint site is a mountain pasture with a clear cut area in the north western part (Fig. 4). Reiteralm is covered with mountain pines, woods and mats (Fig. 3).

3 Field campaign

For validating the accuracy of the snow cover modelling a field campaign was carried out during the winter season 2004/05. The measuring points were located around the meteorological stations of Kühroint and Reiteralm (Figs. 2, 3, 4). The sample points were chosen to give a representative picture of small scale terrain features. At Kühroint, four sample points are located within the forest, whereas 10 sample points are located between the mountain pines and within the canopy stands at Reiteralm. The remaining points are positioned on meadows.

A continuous series of weekly measurements was carried out (at Kühroint and Reiteralm). In some cases the aspired interval could not be maintained because of critical meteorological conditions and high avalanche risk. The National Park rangers measured the snow depth using snow poles and pre-installed staff gauges at the sample points indicated in Figs. 3 and 4. The results of the measurements can be seen in Tables 2 and 3.

4 Models

We used the snow transport model SnowTran-3D (Liston and Sturm, 1998) and the Penn State University – National Center for Atmospheric Research MM5 model (MM5), version 3.3 (Grell et al., 1995).

SnowTran-3D is based on a mass balance equation which describes the temporal variation of snow depth at any grid cell:

$$\frac{d\zeta}{dt} = \frac{1}{\rho s}\left[\rho w P - \left(\frac{dQ_s}{dx} + \frac{dQ_t}{dx} + \frac{dQ_s}{dy} + \frac{dQ_t}{dy}\right) + Q_v\right] \quad (1)$$

Q_s = changes in horizontal mass-transport rates of saltation (kg m^{-1} s^{-1}), Q_t = changes in horizontal mass-transport rates of turbulent suspended snow (kg m^{-1} s^{-1}), Q_v sublimation of transported snow (kg m^{-2} s^{-1}), P = Water equivalent precipitation rate (m s^{-1}), ζ = change of snow depth, t = time (s), x and y horizontal coordinates (m), ρ_s = snow density (kg m^{-3}), ρ_w water density (kg m^{-3}).

The model predicts the horizontal mass transport rates of saltation, changes in horizontal mass transport rates of turbulent suspended snow, sublimation of transported particles and the water equivalent precipitation rate (Liston and Sturm, 1998; Liston and Elder, 2006a) SnowTran-3D has proven its applicability for a wide range of environments from Arctic plains (Liston and Sturm, 1998, 2002) to mountainous terrain (Green et al., 1999; Liston et al., 2000; Prasad et al., 2001; Hiemstra et al., 2002; Hasholt et al., 2003; Bruland et al., 2004; Hiemstra et al., 2006; Bernhardt et al., 2008).

The quasi-physically-based meteorological distribution model MicroMet (Liston and Elder, 2006) is used for the spatial interpolation of measurements of: air temperature, incoming longwave radiation, incoming solar radiation, precipitation, relative humidity, surface pressure, wind direction, and wind speed. As the used wind fields are the core issue of this paper the equations used for the interpolation are displayed in the following (Eqs. 2–10).

$$u = -W \sin(\theta) \tag{2}$$

$$v = -W \cos(\theta) \tag{3}$$

Prediction of the zonal and meridional components of wind speed and direction: u = zonal component, v = meridional component, W = wind speed, θ = wind direction.

$$W = \sqrt{u^2 + v^2} \tag{4}$$

Conversion of meridional and zonal components to W = wind speed [m/s]

$$\theta = \frac{3\pi}{2} - \tan^{-1(\frac{v}{u})} \tag{5}$$

Conversion of meridional and zonal components to θ = wind direction [°]

$$W_W = 1 + \lambda_s \Omega_s + \lambda_c \Omega_c \tag{6}$$

Modification of the wind speed with respect to the topography: W_W = Modification value, λ_s and λ_c = empiric weight factors, Ω_s = scaled slope, Ω_c = scaled curvature.

$$W_t = W_W \times W \tag{7}$$

Prediction of the terrain modified wind speed W_t [m/s] (Liston and Sturm, 1998). W = wind speed, W_W = Modification value

$$\theta_t = \theta + \theta_d \tag{8}$$

Prediction of the terrain modified wind direction θ_t [°] (Ryan, 1977). θ = wind direction, diversion factor θ_d.

$$\theta_d = -0.5\Omega_s \sin[2(\zeta - \theta)] \tag{9}$$

Prediction of the diversion factor θ_d [°] (Ryan, 1977): θ = wind direction, Ω_s = scaled slope, ζ is the slope aspect.

$$W_{ca} = e^{((0.9 \times \mathrm{LAI})(1.0-(0.6\times\rho)/\rho))} \tag{10}$$

Calculation of the wind speed in canopy stands W_{ca} [m/s]. LAI = leaf area index, ρ = vegetation height.

The interpolated wind fields were replaced by physically based MM5 wind fields later on. The MM5 generated wind fields were coupled on SnowTran-3D as a library. Due to performance reasons this library was created in advance and was set into a temporal context to the snow model through the Deutscher Wetterdienst (DWD) Lokalmodell (LM) (Bernhardt et al., 2008). This was possible because of the similarity of MM5 and LM results. For the creation of the wind field library an adapted version of MM5 was utilized (Zängl, 2002, 2003; Bernhardt et al., 2008). This version allows for the production of wind fields with a spatial resolution of 200 m, with the limitation that the

200 m DEM had to be smoothed at some locations (Fig. 5) due to stability requirements of MM5 (Bernhardt et al., 2008). These modifications lead to some inaccuracies which are corrected with the approaches applied here.

5 Downscaling

5.1 Spatial correction

A prerequisite for the model runs at the 30 m scale was a geometric correction of the original 200 m MM5 wind fields. This becomes necessary because of two reasons: a) the modifications at the 200 m DEM for guaranteeing numerical stability of the MM5 model (Bernhardt et al., 2008) resolution dependent shifts of the apexes and minima between 30 m and 200 m DEM. The resulting deviations are especially obvious at very exposed areas like Reiteralm (Fig. 5) and can be observed also within the predicted MM5 wind fields. In the case of Reiteralm the crest of Wartsteinkopf still appears, but not in the position like it is in reality (Fig. 5). Hence the meteorological station Reiteralm 1 is located at the slope in the 200 m dataset as it is at the mountains crest in reality (Fig. 5). Therefore, a validation of predicted data with the help of station measurements becomes erroneous without a correction.

The correction happened via two 2 dimensional second order polynomials:

$$Z' = a1 \times Z^2 + a2 \times S^2 + a3 \times Z + a4 \times S + a5 \times Z \times S + a6 \tag{11}$$

$$S' = b1 \times Z^2 + b2 \times S^2 + b3 \times Z + b4 \times S + b5 \times Z \times S + b6 \tag{12}$$

Equation (11) stands for the new row coordinate and Eq. (12) for the new column coordinate. We used pass points for the determination of the coefficients $a1$–$a6$ and $b1$–$b6$. Under usage of more than six pass points the system of equations becomes over-determined and could be solved with the smallest quadratic deviance between the coefficients $a1$–$a6$ and $b1$–$b6$. So the MM5 DEM and the wind fields could be adapted to the 30 m DEM.

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5.2 Statistical revision

The statistical revision was done in order to prevent of artefacts of the original 200 m pixels in the downscaled 30 m data and in the snow model results, respectively (Fig. 6). A Radial Basis Function (RBF) (Eq. 13) was used for smoothing the wind fields and for eliminating the coarse grid structure by conserving the total amount of energy of each wind field (Fig. 6). RBF is a local statistical technique, calculating predictions from measured points within a defined neighbourhood which is smaller than the total area. As this approach is energy maintaining the modeled 200 m pixel values will be conserved. For verification, mean wind speeds were compared before and after applying this statistical approach between the 200 m pixels and the 30 m pixels which are corresponding to the area of the former 200 m grid cell. The discrepancies were close to zero (Table 4).

The completely regularized spline function that was used is:

$$\phi(r) = -\sum_{n=1}^{\infty} \frac{(-1)^n(\sigma \times r)^{2n}}{n!n} = \ln(\sigma \times r/2)^2 + E_1(\sigma \times r/2)^2 + C_E \tag{13}$$

$\phi(r)$ = Radial basis function, r = the Euclidean distance ($r = \|s_i - s_0\|$ is the distance between the prediction location s_0 and each data location s_i), σ = the smoothing parameter, ln = natural logarithm, E_I = exponential integral function, C_E = Euler constant.

The results of the statistical revision are displayed in Fig. 6 under step 1.

5.3 Inclusion of the height difference between MM5 and 30 m DEM

The coarser resolution of the modified MM5 DEM leads to smoothed elevation minima and maxima. This has a direct effect on the generated wind fields, which also show over- or underestimated wind speeds for the respective locations. For taking this into account the difference of the two DEM was calculated in a thirty meter resolution. In a next step the gradient in wind speed with elevation was calculated for each modelled wind field. Thereby, it was distinguished between two elevation intervals which were significantly dissimilar within the datasets. Thus there is one gradient for the interval from 500 to 1800 m a.s.l. and another for 1800 to 2700 m a.s.l. This separation was necessary because the gradient above 1800 m a.s.l. was much steeper than the gradient for the underlying interval. As a result, this analysis provides a value for the increase of wind speed per meter in elevation for the two intervals. These gradients were then combined with the difference in elevation of the two DEMs. As a result, additional wind speed was generated at locations with positive divergences, and a reduction value was computed at locations where MM5 DEM values are higher than the ones of the 30 m DEM. So the resulting file contains a positive or negative correction value for any 30 m pixel. These values were added to the dedicated statistical reworked MM5 wind field.

5.4 Integration of subgrid topography

Due to the relatively coarse resolution of 200 m most of the small scale sinks and hills of the 30 m DEM were not considered during the MM5 modelling procedure which means that they have not had any influence on the generated wind fields. That makes a subsequent inclusion of this subscale information necessary. Therefore we used algorithms of Liston and Sturm (1998) and Ryan (1977). The algorithm of Liston and Sturm (1998) was originally utilised for the distribution of meteorological station wind speed data, but it can also be applied to the MM5 wind fields if one considers any grid value as a station measurement (Eq. 7). The algorithm of Ryan (1977) was used for modifying the wind direction, again with respect to the 30 m topography (Eqs. 8 and 9). The effect of vegetation on wind speed was considered with the help of Eq. (10).

6 Validation of the MM5 data and application to the snow transport model SnowTran-3D

The correlation between measured and modelled daily wind speeds was greatly improved by the downscaling procedure. The original modelled data correlated with an

r^2 of 0.41 to the measurements while the downscaled set produced an r^2 of 0.63 for the season 2003/2004 (Fig. 7a and b). When analysing the formulas of the trendlines (Fig. 7a and b) it becomes obvious that the downscaled results are much nearer at the 1:1 line than the original results. The original results produced wind speeds, which are much too low in comparison to the measurements which can be explained by the fact that the results were representative for the slope of Reiteralm (Fig. 5) and not for the crest. So, the application of the downscaling routine leads to a considerable improvement of the model results which are now reflecting the local conditions much better than before.

In a next step the information produced via the interpolation scheme was compared with MM5 library results. For the validation of the interpolated values the stations at Reiteralm (Fig. 2) were excluded from the interpolation scheme and used as the basis for comparison between model results and measured values. The interpolation results of wind speed and direction are not substantive. It can be seen that the wind directions at Reiteralm 1 cannot be reproduced by the interpolation scheme (Eqs. 2–10). The probability to compute a correct wind direction is approximately equal to the probability to predict any other wind direction. The convergence of modelled MM5 wind direction with the measurements of Reiteralm is much better than that of the interpolation results. The accuracy of the model is within 10% in about 50% of all cases (the observed period is September 2003 to August 2004) and within 20% in about 75% of the cases.

The interpolated wind speeds (Fig. 9) are commonly to low in comparison to the wind speeds measured at Reiteralm 1. Most of the situations with high wind speeds were not reproduced by the interpolation routine (Fig. 9). This is because beside of the excluded Reiteralm 1 station, there is no other meteorological station at a higher elevation which results in an even elevation wind speed gradient.

When analysing MM5 and measured wind speed it becomes obvious that MM5 delivers reasonable results here (Fig. 10). MM5 wind speeds are on the same level as the measurements and the course of the measurements is reproduced very well.

7 Methodology of the snow modelling

SnowTran-3D runs were performed for the winter season 2004/2005 with a temporal resolution of one hour and a spatial resolution of 30 m. The required input parameters, precipitation, humidity, radiation, wind speed, wind direction, air pressure and air temperature were delivered by six meteorological stations (Table 1). We used downscaled MM5 wind fields for a) proofing their performance in comparison with interpolated measurements in the direct environment of meteorological stations and b) for demonstrating the advantages of these fields at steep terrain. The well instrumented sites Reiteralm and Kühroint were selected. Reiteralm has an area of about 2 km^2. The two available automatic stations were installed for observing snow transport processes from the higher situated meteorological station 2, to station 3 (Fig. 2). At this special site it should be shown that the SnowTran-3D/MM5 couple is able to reproduce the recorded transport events. At Kühroint, which is sheltered from the wind, the correct reproduction of no transport conditions should be proofed.

For the first model run at Reiteralm the parameterisation of the vegetation classes was adopted from Liston and Sturm (1998). After that, the vegetation type "mountain pine" was introduced and modified with respect to field measurements and to model results. In addition, a vegetation type "sporadic trees" was created for areas with sparse canopy stands. In a next step the 30 m results were compared to Landsat ETM+ data and finally snow transport processes in the surrounding of the Blaueis glacier were discussed. The different 30 m runs will be indicated by two different abbreviations. The runs will be called: INTER_30 (SnowModel/SnowTran-3D/interpolated wind fields) and MM5_30 (SnowModel/SnowTran-3D/MM5wind fields) in the following sections.

8 Results and discussion

The results at Reiteralm showed a satisfying convergence between modelled and measured values of snow depth (Fig. 11). However, the modelled snow depth was gener-

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ally overestimated at the upper part of Reiteralm and underestimated at the lower parts (Fig. 11). The variance between the sample points could be reproduced to some extent, but is generally too small within the model results (Fig. 11).

Experiences of the Avalanche Warning Service of Bavaria which has observed this site for a over ten years indicate that considerable amounts of snow are often blown from the upper (characterised by sample points 1–8, Fig. 3) to the lower part of the site (sample points 14 and 15, Fig. 3). This experience is confirmed by the snow depth measurements of the automatic meteorological stations Reiteralm II and III but was only reproduced to some degree by the snow transport model. Hence, the transport processes were underestimated when using the existing vegetation snow holding capacities.

By adding the new vegetation types and MM5 wind fields the model results could be improved at the upper part of the Reiteralm, but there are only minor changes at the lower part. The analysis revealed that this is due to the forest which subdivides Reiteralm into two parts. The model treats this forest as a physical barrier which blocks snow transport. The introduction of the vegetation class sporadic trees resulted in no improvement. This can be attributed to the general model setup. To allow snow transport over the forest land cover, two different wind velocity layers would be required but only one is available.

A difference in the model results caused by the use of modelled MM5 versus the interpolated wind fields could only be found at the upper stations. The other stations are close to the forest or within the forest which causes the differences to be negligible.

9 Results Kühroint

Figure 4 shows three sample points at Kühroint. Point N) is located at the edge of the forest at the northern part of Kühroint; point F is located at the clear cut area, and point K can be found on the meadows in the western part of the area. The three points represent the range of model results of snow depth versus observational data:

maximum overestimation N), best fit K) and maximum underestimation F). In general, the overall variance of the modelled data is too small with respect to the snow depth differences between the sample points. The variation between the modelled pixels was especially low at the centre parts of Kühroint. This might be due to the DEM used in this study which describes the centre of Kühroint, which is undulated in reality, as an almost completely flat area. This discrepancy between real and modelled topography is likely one reason for the difference between measurements and model results. Nevertheless there are some other possible reasons, like a misinterpretation of the snow density.

It is important to note that there are almost no differences in amount and timing of snow transport between the MM5 wind fields and interpolated wind fields, for the observed winter season. This proves the applicability of the MM5 wind fields, because the wind speed and direction measured by the meteorological station Kühroint should be representative for the whole clearance. As a result, the MM5 wind fields can be regarded as representative for Kühroint.

10 Spatial validation using Landsat ETM+ data

As the results at Reiteralm and Kühroint have shown approximately no differences between the results generated with the interpolation routine and MM5 wind fields a spatial comparison of the results on the basis of remotely sensed data was progressed. The small negligible differences of the results are due to the fact that the test sites are located below of 1800 m a.s.l. were the differences between MM5 and interpolated wind speeds are small (Bernhardt et al., 2008) (Fig. 13).

The 30 m results correspond to the extent and support of Landsat ETM+ data. Hence, a direct comparison of the data becomes possible. In a first step, the spatial extent of the mapped and modelled snow cover was compared for both available dates. As it is impossible to quantify the SWE distribution via the available optical remotely sensed data a different way to validate the model results was chosen. Areas which are snow free within the Landsat images but are predicted to be snow covered by the model were detected in a first step. After than INTER_30 and MM5_30 SWE depths were compared with a snow model stand alone model run (without transport routine) which is called run_baseline from now on. When using the run_baseline results as basis one can determine to which extent the results could be improved by including the blowing snow model algorithm in INTER_30 and MM5_30.

The results of INTER_30 and MM5_30 are virtually identical with respect to the snow line and can be discussed on the basis of the MM5_30 results. A comparison of classified versus modelled snow cover from MM5_30 has shown that the model once again produced a snow cover that was too homogenous (Fig. 14a to d). This can be attributed to an inability of the model to reproduce the extent of the real transport rates or to the fact that the model is not able to predict all processes leading to the real distribution like preferential snow distribution and snow slides. As a first step, the extent of the predicted snow cover from MM5_30 was compared to the remotely sensed data. 86 percent of the model grids are in agreement with the produced snow map for 28 April 2004 and 88 percent for 30 May 2004. 5 percent of the pixels are classified as snow but do not show a snow cover within the modelled data on 28 April 2004 (4 percent at 30 Mai) while 9 percent (for both dates) of the modelled grid cells are predicted to be snow covered but are snow free within the classification.

In a subsequent step, nine validation areas were selected within a Landsat April image and six for a May image (both of the winter season 2003/04) (Figs. 15 and 16, Tables 5 and 6) for the comparison with the remotely sensed data. The areas were totally snow free within the Landsat image but snow covered within the model results. The values shown in Tables 5 and 6 are averages for the whole areas Results show that SnowTran-3D is overestimating the SWE depth significantly on 28 April 2004 and slightly on 30 May 2004 (Tables 5 and 6). It is also obvious that SnowTran-3D with interpolated wind fields does not lead to a significant improvement of the results. Moreover, it could be seen that the accuracy of the results can even decline when using interpolated fields (Table 5: area 7 and 9; Table 6: area 2). SnowTran-3D runs with downscaled MM5 wind fields on the other hand show improvements for all results. On

28 April the results were improved by approximately 23% while results on 30 May were improved by 60% when using the MM5 wind fields.

Further analysis of the test areas has shown that the reduction of the SWE depth modelled in comparison to run_baseline shows no clear trend or pattern over the areas. Moreover, it could be seen that the snow is redistributed within the areas in INTER_30. This is caused by the comparatively low interpolated wind speeds and insufficient wind direction fields used in INTER_30. In contrast, the results of MM5_30 show a trend within the spatial pattern; the SWE depth is particularly reduced at higher elevations and in the direction of the next crest. This conforms to the expectations and corresponds to observations one can make in nature (Fig. 17c) where it can be seen that the SWE depth are especially reduced on the windward site of the crest regions (Fig. 17a and b).

Plattner et al. (2006) have applied a statistical analysis of the SWE distribution at Vernagtferner and have found that the SWE distribution is very likely dependent on the wind conditions and on wind induced snow transport. However, a quantitative estimation of the transported amounts was not possible. The work presented here shows that a numerical calculation of the transported SWE amounts is possible via the presented scheme. The Blaueis glacier serves as an example. It could be seen that the amount of the transported SWE considerably depends on the used model scale and wind simulation method. Principally, it can be stated that the use of SnowTran-3D does not lead to any transport rates from and to the glacier if interpolated wind fields are used. When MM5 wind fields are used on the other hand, significant transport processes can be observed. The MM5_30 runs produce a maximum SWE gain per pixel of 2140 mm SWE. The average contribution of windblown snow over the total glacier area is 220 mm SWE.

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11 Discussion

The results at Reiteralm and Kühroint fit well to the measurements. Results at Reiteralm could be partly improved by the inclusion and adjustment of additional vegetation classes. At Kühroint the results do not differ between the used methods (MM5 or interpolated wind fields), due to the wind conditions at Kühroint in the winter season 2004/05. The mean wind speed was below 1 m/s and only 69 h with wind speeds of more than 3 m/s were registered, thus we could assume low snow transport rates. Hence it is a satisfying result that SnowTran-3D is not generating higher transport rates under usage of the MM5 wind fields because this would indicate a systematic misinterpretation of the local situation at Kühroint.

The minor differences between the two methods at both sites are in line with the expectations according to Bernhardt et al. (2008). They have found that the MM5 and the interpolated wind fields are significantly different for heights from 1800 m a.s.l. upwards. Nevertheless the coincidence between SnowTran-3D results which could be achieved in the direct neighbourhood of an anemometer and under usage of interpolated or MM5 wind fields show that MM5 data is applicable. The overall performance of the MM5 approach is mostly similar or better than the performance of SnowTran-3D in combination with the interpolation routine.

The comparison to the remotely sensed data has shown that the modelled snow cover is too homogenous with respect to the Landsat ETM+ data. Nevertheless, the application of MM5 wind fields has improved the performance of the snow transport routine in a significant way when considering the results presented in Tables 5 and 6. The results obtained at Blaueis glacier have shown that the quantitative calculation of wind induced transport of snow from neighbouring areas to adjacent glacier areas becomes possible via the presented scheme at the 30 m scale. A validation of the transported snow amounts at Blaueis glacier or at other well instrumented glaciers like the Vernagtferner is the subject of future work. The obtained knowledge about gain rates could be crucial for a better understanding of the mass balance of the respective glaciers.

As the accuracy of the presented approach is not dependent on the general location of the observed area, it could be a helpful alternative for Alpine environments, independent whether they are well, bad or not equipped.

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References

Balk, B. and Elder, K.: Combining binary decision tree and geostatistical methods to estimate snow distribution in a mountain watershed, Water Resour. Res., 36, 13–26, 2000.

Barry, R. G.: Mountain Weather and Climate. Routledge, Taylor & Francis Books Ltd, 1992.

Bernhardt, M., Strasser, U., Zängl, G., and Mauser, W.: Using MM5-derived wind fields for the modelling of snow transport processes, in: Abstracts of the 3rd Symposium for Research in Protected Areas, 2005.

Bernhardt, M., Zängl, G., Liston, G. E., Strasser, U., and Mauser, W.:. Using wind fields from a high resolution atmospheric model for simulating snow dynamics in mountainous terrain, Hydrol. Processes, accepted, 2008.

Bowling, L. C., Pomeroy, J. W., and Lettenmaier, D. P.: Parameterization of Blowing-Snow Sublimation in a Macroscale Hydrology Model, J. Hydrometeorol., 5, 745–762, 2004.

Bruland, O., Liston, G. E., Vonk, J., Sand, K., and Killingtveit, A.: Modelling the snow distribution at two high arctic sites at Svalbard, Norway, and at an Alpine site in central Norway, Nordic Hydrology, 35, 191–208, 2004.

Déry, S. J. and Yau, M. K.: A Bulk Blowing Snow Model, Bound. Lay. Meteorol., 93(2), 237–251, 1999.

Doesken, N. J. and Judson, A.: The Snow Booklet: A guide to the science, climatology, and measurement of snow in the United States, Colorado State University, Fort Collins, CO, 1996.

Doorschot, J.: Mass transport of drifting snow in high alpine environments, http://e-collection.ethbib.ethz.ch/show?type=diss&nr=14515, 2002.
Eidsvik, K. J., Holstad, A., Lie, I., and Utnes, T.: A Prediction System for Local Wind Variations in Mountainous Terrain, Bound.-Lay. Meteorol., 112(3), 557–586, 2004.
Essery, R. L. H., Li, L., and Pomeroy, J. W.: A Distributed Model of Blowing Snow over Complex Terrain, Hydrol. Process., 13, 2423–2438, 1999.
Essery, R. L. H.: Spatial statistics of windflow and blowing-snow fluxes over complex terrain, Bound.-Lay. Meteorol., 100, 131–147, 2001.
Greene, E. M., Liston, G. E., and Pielke, R. A.: Simulation of above treeline snowdrift formation using a numerical snow-transport model, Cold Regions Sci. Technol., 30, 135–144, 1999.
Grell, G. A., Dudhia, J., and Stauffer, D. R.: A description of the fifth generation Penn State/NCAR mesoscale model (MM5), Technical report, National Centre for Atmospheric Research, Boulder, Colorado, USA, 1995.
Hasholt, B., Liston, G. E., and Knudsen, N. T.: Snow-distribution modelling in the Ammassalik region, south east Greenland, Nordic Hydrol., 34, 1–16, 2003.
Hiemstra, C. A. A., Liston, G. E., and Reiners, W. A.: Snow redistribution by wind and interactions with vegetation at upper treeline in the Medicine Bow Mountains, Wyoming, USA, Arctic Antarctic and Alpine Res., 34, 262–273, 2002.
Hiemstra, C. A., Liston, G. E., and Reiners, W. A.: Observing, modelling, and validating snow redistribution by wind in a Wyoming upper treeline landscape, Ecol. Model., 197, 35–51, 2006.
Lehning, M., Doorschot, J., Raderschall, N., and Bartelt, P.: Combining snow drift and SNOWPACK models to estimate snow loading in avalanche slopes, Snow Eng., 113–122, 2000.
Lehning, M., Völksch, I., Gustafsson, D., Nguyen, T. A., Stähli, M., and Zappa, M.: ALPINE3D: a detailed model of mountain surface processes and its application to snow hydrology, Hydrol. Processes, 20(10), 2111–2128, 2006.
Liston, G. E.: Local Advection of Momentum, Heat, and Moisture during the Melt of Patchy Snow Covers, J. Appl. Meteorol., 34, 1705–1715, 1995.
Liston, G. E. and Sturm, M.: A snow-transport model for complex terrain, J. Glaciol., 44, 498–516, 1998.
Liston, G. E., Winther, J. G., Bruland, O., Elvehoy, H., Sand, K., and Karlof, L.: Snow and blue-ice distribution patterns on the coastal Antarctic Ice Sheet, Antarctic Sci., 12, 69–79, 2000.

Liston, G. E. and Sturm, M.: Winter Precipitation Patterns in Arctic Alaska Determined from a Blowing-Snow Model and Snow-Depth Observations, J. Hydrometeorol., 3, 646–659, 2002.
Liston, G. E.: Representing Subgrid Snow Cover Heterogeneities in Regional and Global Models, J. Climate, 17, 1381–1397, 2004.
Liston, G. E. and Elder, K.: A distributed snow-evolution modeling system (SnowModel), J. Hydrometeorol., 7, 1259–1276, 2006a.
Plattner, C., Braun, L., and Brenning, A.: The spatial variability of snow accumulation at Vernagtferner, Austrian Alps, in Winter 2003/2004, Zeitschrift fr Gletscherkunde und Glazialgeologie, 39, 43–57, 2006.
Prasad, R., Tarboton, D. G., Liston, G. E., Luce, C. H., and Seyfried, M. S.: Testing a blowing snow model against distributed snow measurements at Upper Sheep Creek, Idaho, United States of America, Water Resour. Res., 37, 1341–1356, 2001.
Pomeroy, J. W., Gray, D. M., and Landine, P. G.: The Prairie Blowing Snow Model – characteristics, validation, operation, J. Hydrol., 144, 165–192, 1993.
Pomeroy, J. W., Gray, D. M., Shook, K. R., Toth, B., Essery, R. L. H., Pietroniero, A., and Hedstrom, N.: An evaluation of snow accumulation and ablation for land surface modelling, Hydrol. Process., 12, 2339–2367, 1998.
Ryan, B. C.: A mathematical model for diagnosis and prediction of surface winds in mountainous terrain, J. Appl. Meteorol., 16, 571–584, 1977.
Winstral, A. and Marks, D.: Simulating wind fields and snow redistribution using terrain-based parameters to model snow accumulation and melt over a semi-arid mountain catchment, Hydrol/ Processes, 16, 3585–3603, 2002.
Zängl, G.: An Improved Method for Computing Horizontal Diffusion in a Sigma-Coordinate Model and Its Application to Simulations over Mountainous Topography, Mon. Weather Rev., 130, 1423–1432, 2002.
Zängl, G.: Orographic Gravity Waves Close to the Nonhydrostatic Limit of Vertical Propagation, J. Atmos. Sci., 60, 2045–2063, 2003.

Table 1. Meteorological stations which were used, their abbreviations, geographical coordinates, elevation, and meteorological recordings: wind speed (WS), wind direction (WD), temperature (T), humidity (H), snow height (SH), global radiation (GR), and precipitation (P).

Station	Elev (a.s.l.)	Long (deg)	Lat (deg)	Temporal resolution	Parameters deserved
Jenner I	1200 m	13.01926	47.58648	10 min	T, TS0, H, SH
Kühroint	1407 m	4 572 314	5 270 625	10 min	T, H, GR, RR, WS, WD, P, SH
Reiter Alm I	1755 m	12.80532	47.65132	10 min	WS, WD
Reiter Alm II	1670 m	12.80984	47.64949	10 min	T, H, SH
Reiter Alm III	1615 m	12.81133	47.64720	10 min	T, H, GR, P, SH
Schönau	617 m	12.98332	47.60941	10 min	T, H, GR, WS, WD, P

Table 2. Snow depth (cm) at the sample points at Reiteralm (2004/2005).

sample point	8 Feb 2005	15 Feb 2005	23 Feb 2005	2 Mar 2005	10 Mar 2005	14 Mar 2005	23 Mar 2005	30 Mar 2005	5 Apr 2005	14 Apr 2005
1	76	126	116	114	104	101	74	57	48	39
2	138	189	175	174	204	176	124	97	70	58
3	151	196	179	175	183	172	118	100	85	83
4	133	186	173	167	184	170	125	97	89	82
5	146	204	188	185	202	187	139	112	105	101
6	140	178	164	158	196	172	126	122	105	94
7	173	214	198	119	235	212	155	141	119	117
8	94	144	131	125	139	122	80	59	36	35
9	147	168	163	156	197	174	119	95	48	72
10	220	260	231	231	235	200	154	141	118	109
11	169	218	192	180	210	230	122	107	53	56
12	202	257	215	209	255	232	157	130	115	101
13	176	230	209	198	250	234	161	138	118	118
14	224	264	240	240	305	270	209	178	157	157
15	230	259	238	238	320	320	218	197	160	149

Table 3. Snow depth (cm) at the sample points at Kühroint (2004/2005) (−9999 = missing value).

sample point	8 Feb 2005	15 Feb 2005	22 Feb 2005	2 Mar 2005	8 Mar 2005	15 Mar 2005	22 Mar 2005	29 Mar 2005	12 Apr 2005	19 Apr 2005
A	128	114	156	133	146	145	102	80	81	51
B	175	161	165	174	188	189	139	115	102	78
C	95	73	86	95	102	108	53	21	40	0
D	111	−9999	128	132	240	105	−9999	71	0	0
E	173	153	160	168	183	188	125	102	92	62
F	165	147	155	165	173	175	120	101	83	58
G	164	152	160	166	178	178	125	105	94	73
H	183	176	177	180	200	207	155	142	135	113
I	121	110	123	126	142	146	105	99	72	46
J	76	82	90	85	100	95	60	38	0	0
K	122	113	120	124	140	142	96	69	59	40
L	177	63	166	176	189	202	154	136	123	89
M	88	87	95	105	116	122	60	53	23	0
N	86	77	84	87	100	108	83	29	0	0
O	165	149	146	146	169	177	127	104	92	66

Table 4. Column I: Mean value of all 220 wind fields between the average value of the original and the modified MM5 wind speeds. Column II: Maximal observed difference between original and modified MM5. Column III: Minimal observed difference.

Mean deviation	Maximal deviation	Minimal deviation
0.003 [m/s]	0.02 [m/s]	0.00 [m/s]

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Table 5. Comparison between SnowTran-3D results generated with interpolated wind fields as well as MM5wind fields. The values belonging to the areas highlighted in Fig. 15. The areas are snow free in reality, the values within the table showing the improvement of the SnowTran-3D results when the transport routine is used in comparison to results generated without a transport routine.

Improvement when using:	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8	Area 9
INTER_30[%]	5%	3%	3%	0%	2%	2%	−100%	0%	−2%
MM5_30[%]	28%	26%	9%	16%	30%	26%	12%	22%	26%
INTER_30[mm]	−3 mm	−2 mm	−1 mm	0	−2 mm	−2 mm	+132 mm	0 mm	+2 mm
MM5_30[mm]	−18 mm	−20 mm	−3 mm	−18 mm	−26 mm	−23 mm	−16 mm	−22 mm	−21 mm

Table 6. Comparison between SnowTran-3D results generated with interpolated wind fields as well as MM5wind fields. The values belonging to the areas highlighted in Fig. 16. The areas are snow free in reality, the values within the table showing the improvement of the SnowTran-3D results when the transport routine is used in comparison to results generated without a transport routine.

Improvement when using:	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
INTER_30[%]	0%	−2	1%	0%	1%	12%
MM5_30[%]	80%	46%	63%	55%	35%	86%
INTER_30[SWE]	0 mm	+2 mm	−1 mm	0 mm	−1 mm	−2 mm
MM5_30 [SWE]	−78 mm	−43 mm	−39 mm	−84 mm	−30 mm	−31 mm

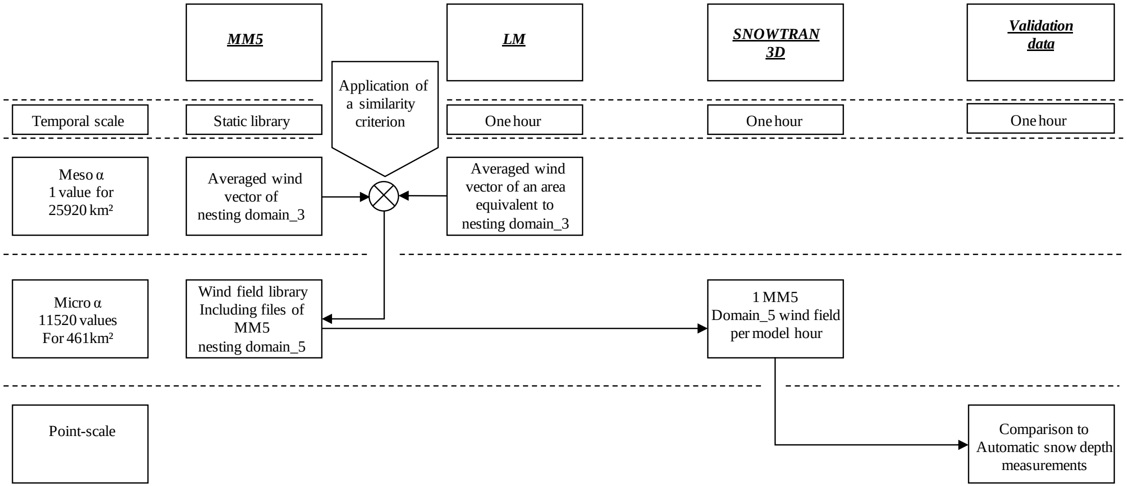

Fig. 1. Schematic diagram showing the different models used for this paper. It also gives an overview of the scales involved and the temporal resolution of the different components. LM stands for the German Weather Service Local Model.

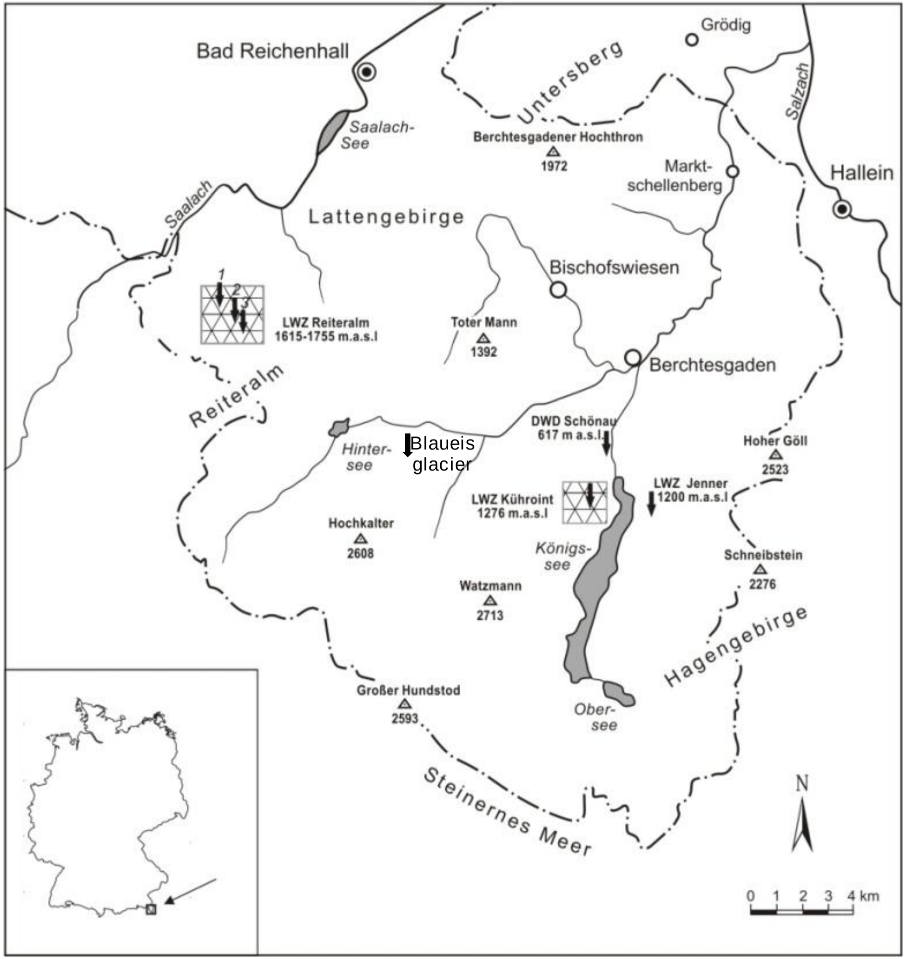

Fig. 2. Test site (National Park Berchtesgaden) (Bayerisches Landesvermessungsamt 1994, modified). The locations of Reiteralm 1, 2 and 3 are marked with arrows.

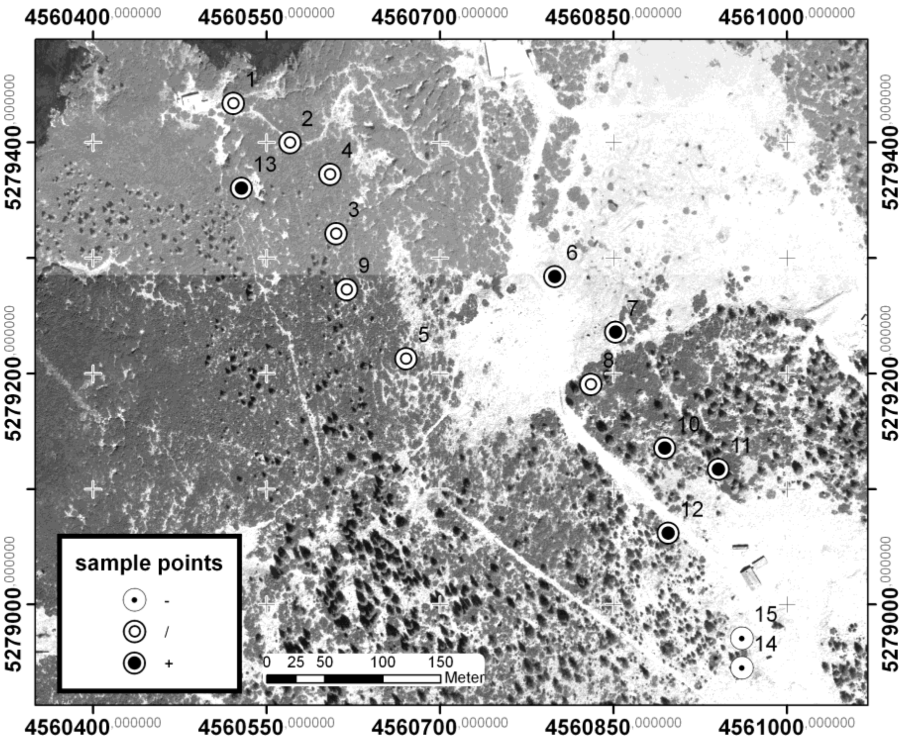

Fig. 3. Sample points Reiteralm 2004/2005.

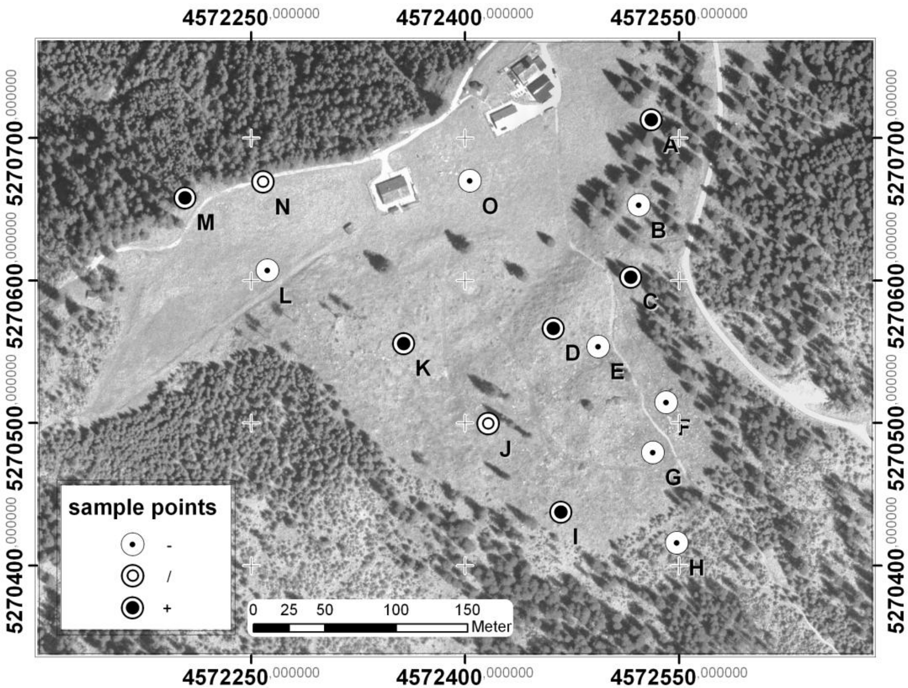

Fig. 4. Sample points at Kühroint 2004/2005.

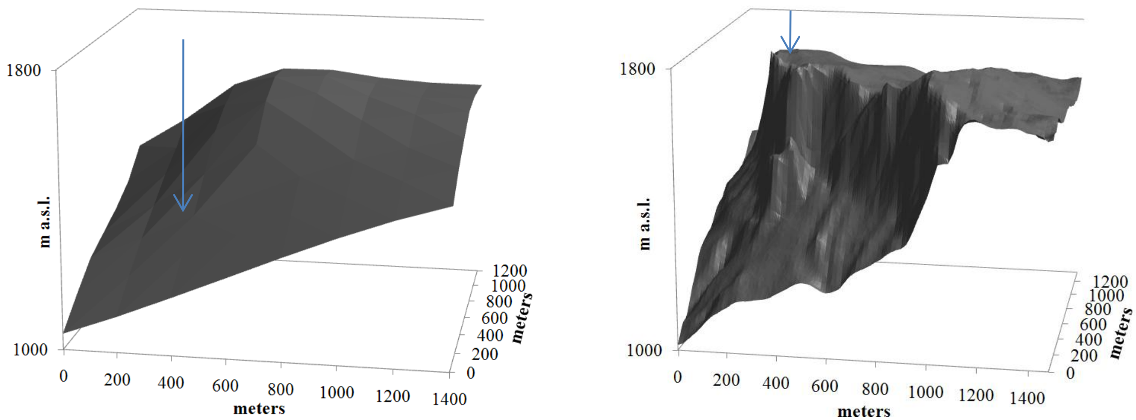

Fig. 5. The smoothed Reiteralm area (marked with an arrow) within the MM5 DEM (200 m resolution) compared to the National Park DEM (10 m resolution).

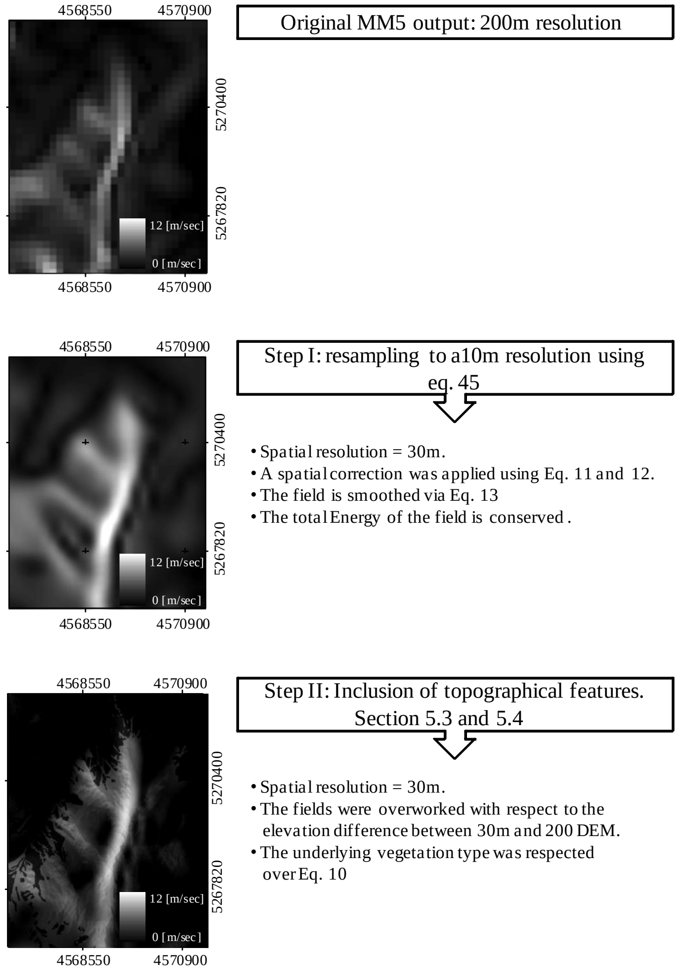

Fig. 6. I: Cutout of the original wind field (200 m) containing the Watzmann massif. II and III: Downscaling steps and results.

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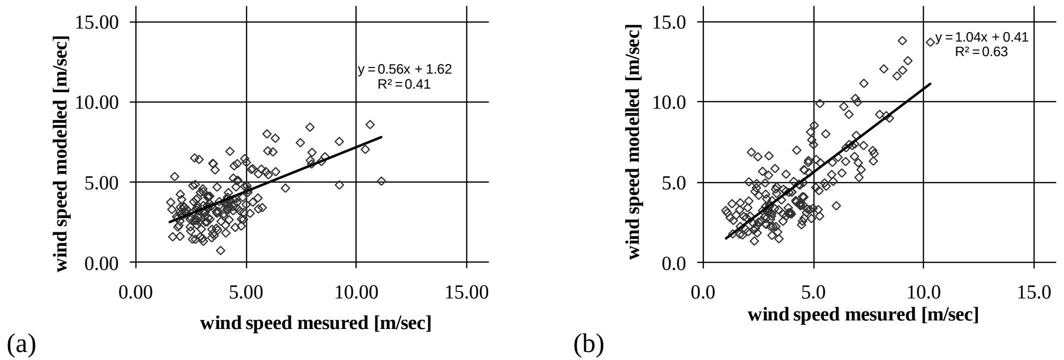
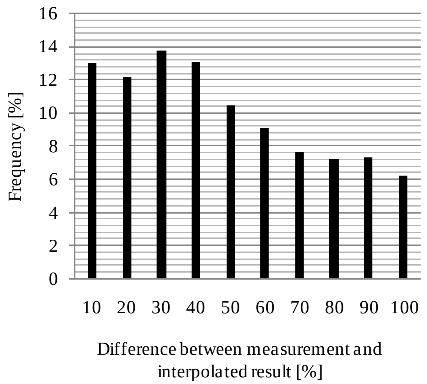


Fig. 7. (a) Correlation between MM5 results and station recordings before the downscaling procedure (Reiteralm I, daily resolution) **(b)** Correlation between MM5 results and station recordings after the downscaling procedure. The regression line is forced through the origin.



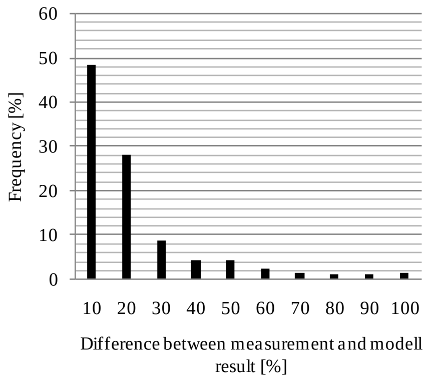


Fig. 8. (a) Comparison of measured and interpolated wind direction at Reiteralm I, **(b)** Comparison of measured and MM5 wind direction at Reiteralm I.

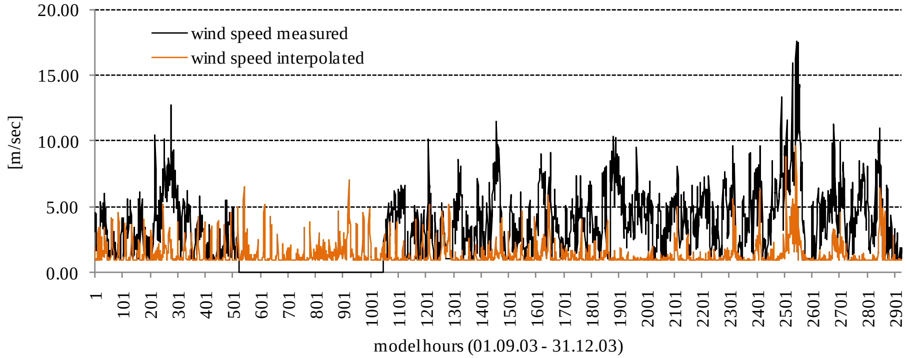


Fig. 9. Comparison of measured and interpolated wind speed at Reiteralm I.

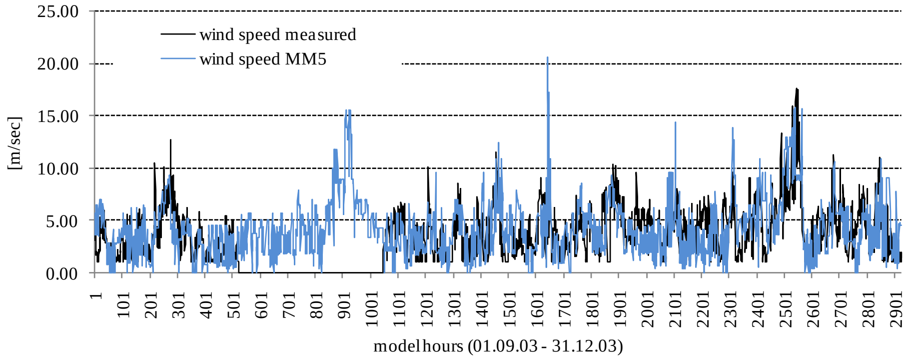


Fig. 10. Comparison of measured and MM5 wind speed at Reiteralm I (1 September 2003–31 December 2003).

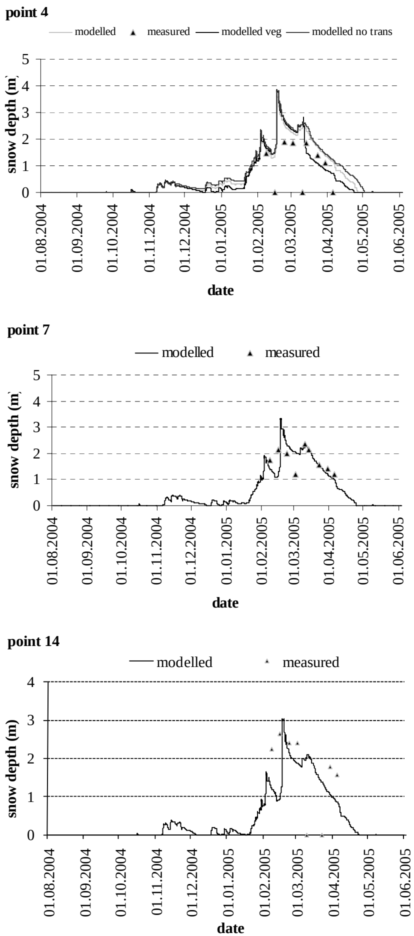


Fig. 11. (a) is representative for the upper part of Reiteralm. **(b)** For the central region and **(c)** For the lower part.

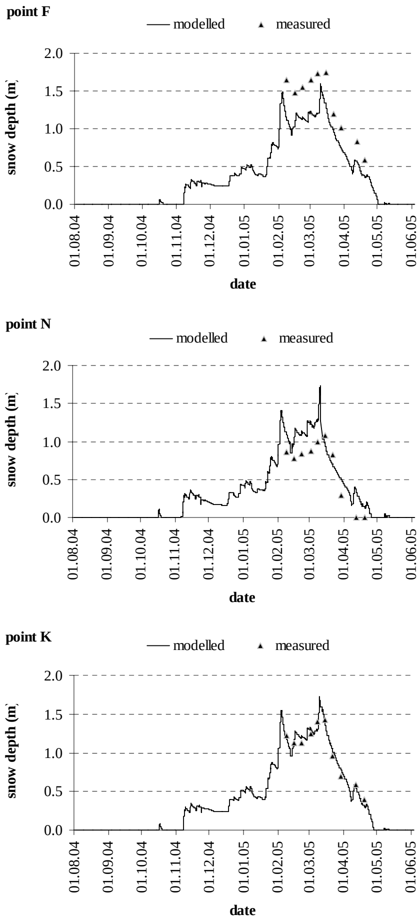


Fig. 12. Three representative points at Kühroint. **(a)** maximum underestimation, **(b)** maximum overestimation, **(c)** best fit.

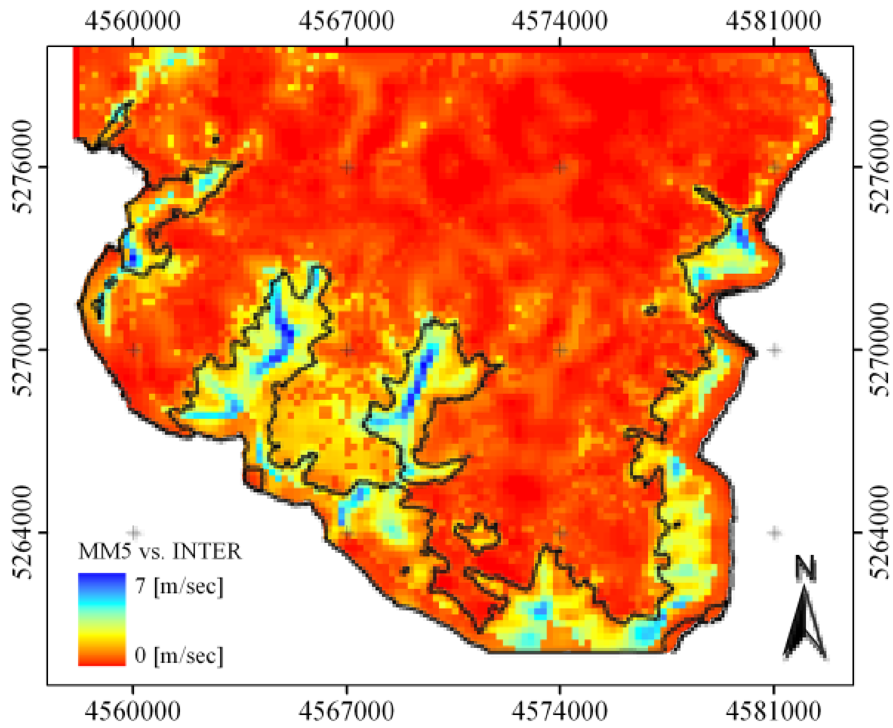


Fig. 13. Difference between the averaged interpolated and MM5 wind speed for the winter season 2003/2004 (The black line is the 1800 m a.s.l. contour).

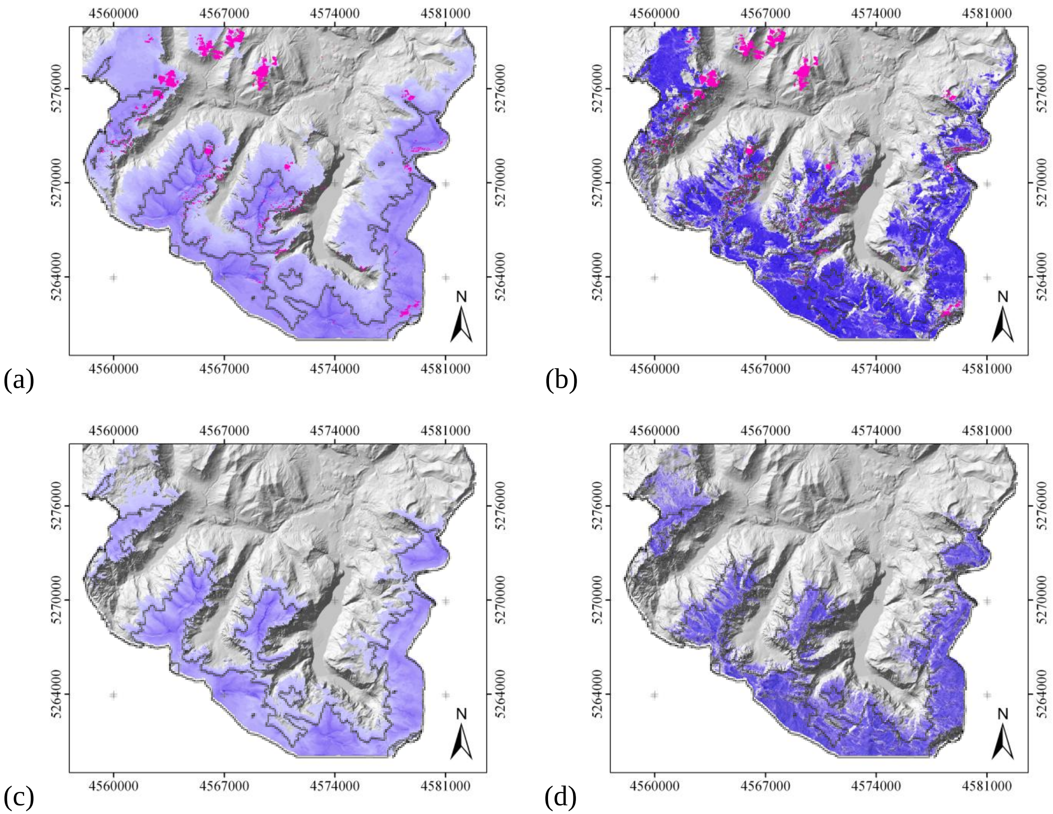


Fig. 14. **(a)** Modelled snow cover of 28 April 2004; **(b)** NDSI map of the same date; **(c)** modelled snow cover of 30 Mai 2004; **(d)** NDSI map of Mai the same date. (The black line is the 1800 m a.s.l. contour).

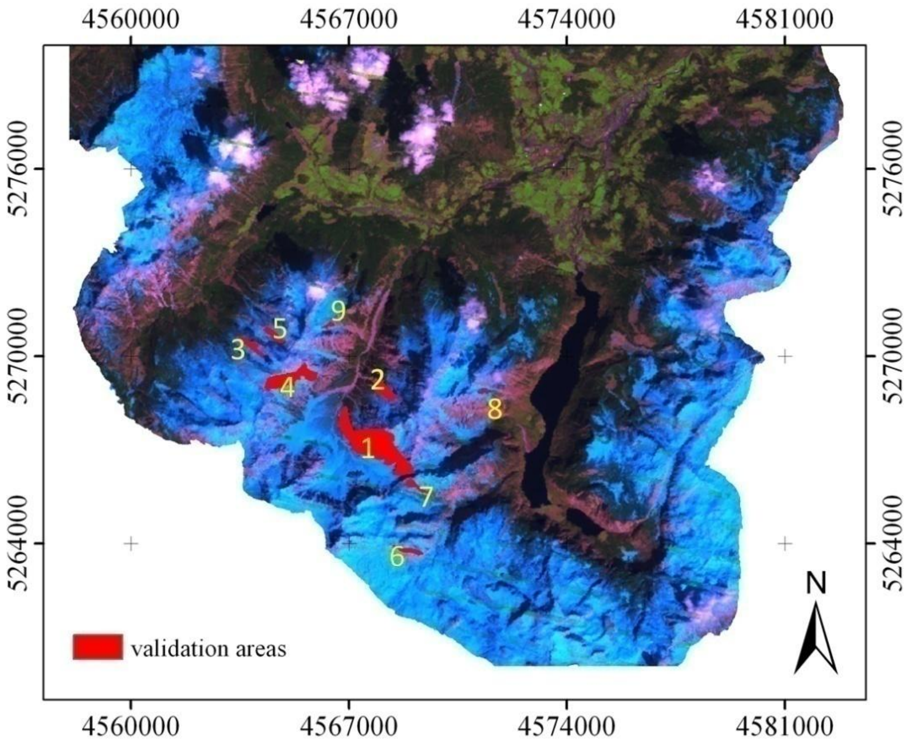


Fig. 15. Validation areas of 28 April 2004. Blue: Snow covered regions. Red: test areas (Bands: 5,4,3).

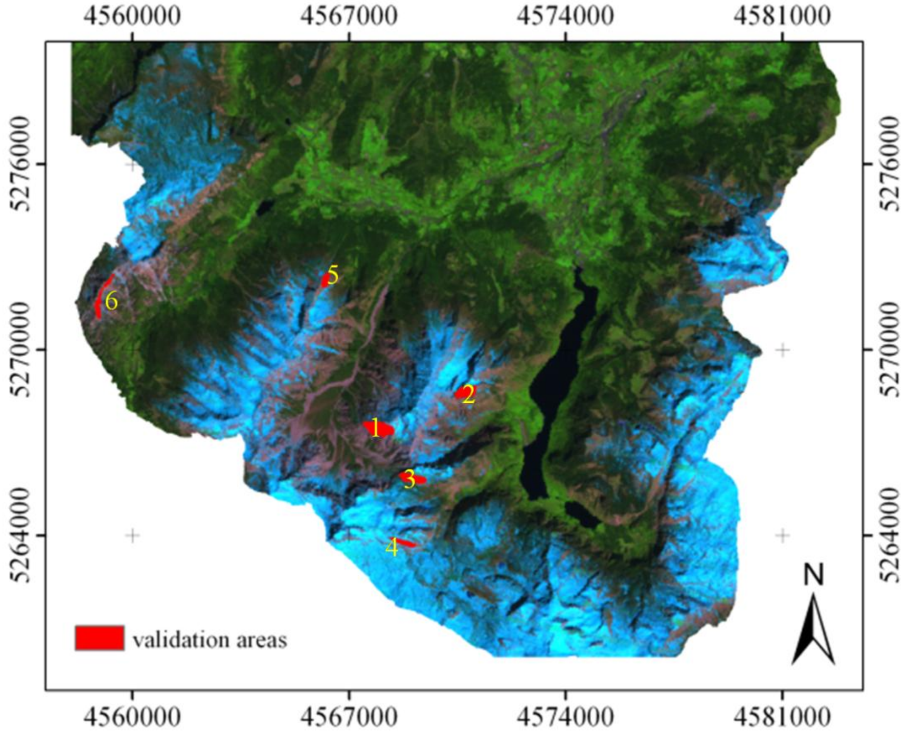


Fig. 16. Validation areas of 30 Mai 2004. Blue: snow cover. Red: test areas (Bands: 5,4,3).

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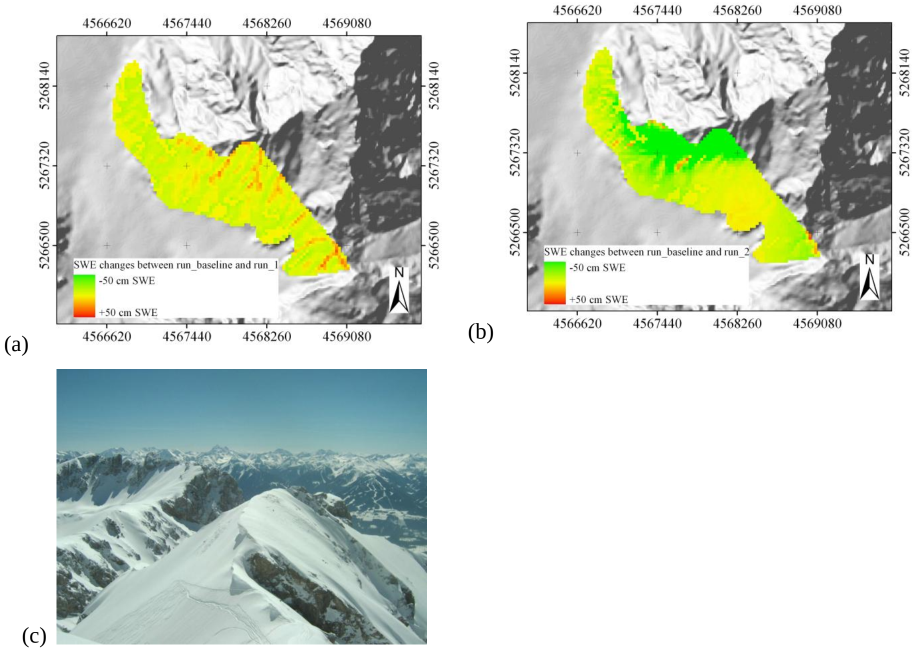

Fig. 17. **(a)** Comparison of run_baseline and run_1 results on 28 April 2004, **(b)** comparison between run_baseline and run_2 at the same date. **(c)** picture of a crest were the snow cover on the windward site (right) is reduced considerably by snow transport processes.

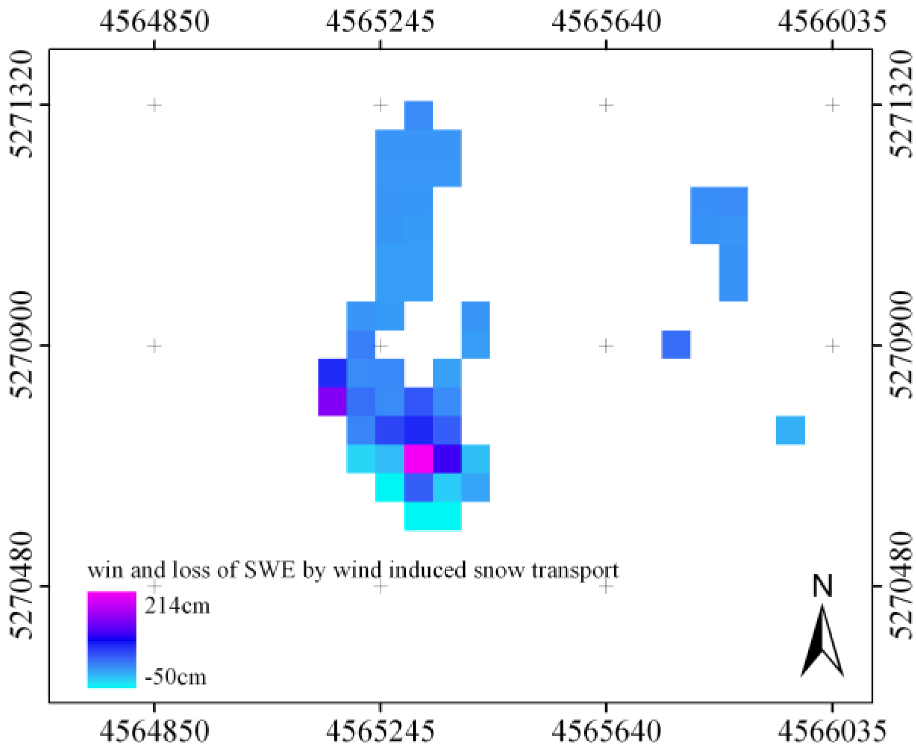

Fig. 18. Predicted loss and gain of SWE due to wind induced snow transport at Blaueis glacier.