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pSNOWPACK: a forecasting tool for avalanche warning services

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Abstract

Avalanche danger is often estimated based on snow cover stratigraphy and snow stability data. In Canada, single forecasting regions are very large (>50 000 km^2) and snow cover data are often not available. To provide additional information on the snow cover and its seasonal evolution the Swiss snow cover model SNOWPACK was therefore coupled with a regional weather forecasting model GEM15. We assess the capability of this model chain (pSNOWPACK) to forecast three key factors of snow cover instability at a single point: new snow amounts, surface hoar formation and crust formation. The output of GEM15 was compared to meteorological data from Mt. Fidelity, British Columbia, Canada, for five winters between 2005 and 2010. Forecasted precipitation amounts were generally over-estimated. The forecasted data were therefore filtered and used as input for the snow cover model. Comparison between the model output and manual observations showed that after pre-processing the input data the snow depth, new snow events and amounts were well modelled. Relevant critical layers, i.e. melt-freeze crusts and surface hoar layers were reproduced. Overall, the model chain pSNOWPACK shows promising potential as a forecasting tool for avalanche warning services in Canadian data sparse areas and could thus well be applied to similarly large regions elsewhere.

1 Introduction

Avalanche warning services usually assess the snow cover stability based on avalanche observations as well as on weather and manual snow cover observations. This now-cast is usually combined with the weather forecast to estimate the avalanche danger of the next day. Forecasting for the next day is often challenging since it strongly relies on the quality of the now-cast and on the mountain weather forecast, which contains some uncertainty especially for complex terrain. Snow cover observations are time consuming and are often not feasible due to bad weather or unfavourable snow cover conditions. This often results in very little or no information about the state of the snow cover especially if the forecasting regions are very large.

The Canadian Avalanche Centre (CAC) is forecasting for 20 regions in western Canada. These regions range from 200 km^2 to over 50 000 km^2 covering a total area of about 345 000 km^2. The CAC has access to about 250 automatic weather stations (AWS). The data from these stations are used operationally by the avalanche warning service (K. Klassen, personal communication, 2011). Field observations such as avalanche occurrence or stability test results are usually reported daily by avalanche professionals working for helicopter/snowcat skiing operations or avalanche control programs for parks or highways.

The average area per weather station in Canada is 1345 km^2 and in Switzerland 100 km^2, i.e. a much higher density of weather station compared to Canada. In Canada weather stations are often located close to highway corridors and not in the alpine or avalanche terrain. The area covered by, e.g. heliskiing operations, are usually small compared to the corresponding forecasting region in which they are located. In addition, within some of the Canadian forecasting regions almost no weather stations exit and no skilled observers visit these areas on a regular basis, e.g. the North Rockies. For these so called data-sparse areas almost no information on weather and snow cover conditions is available, making the now-cast and the forecast challenging.

Snow cover models became more and more important for avalanche warning services in Europe. These physical based models use meteorological parameter as input data. The two most advanced snow cover models for avalanche forecasting are the Swiss snow cover model SNOWPACK (Lehning et al., 2002a, b; Lehning and Fierz, 2008) and the French model-chain SAFRAN-CROCUS-MEPRA (Brun et al., 1989, 1992; Durand et al., 1999).

The one-dimensional snow cover model SNOWPACK treats snow as a three-component material consisting of ice, water and air. Changes of the snow cover, i.e. mass, momentum and energy exchange are calculated using Lagrangian Finite Element methods. If the meteorological input is provided by AWS, only a now-cast is possible (Lehning, 1999).

Three numerical models form the model-chain SAFRAN-CROCUS-MEPRA. The first model SAFRAN provides the meteorological input parameter from various sources such as numerical weather prediction models (NWP) or automatic weather stations. The snow cover model CROCUS calculates changes of the snow cover using finite difference methods. MEPRA calculates additional snow mechanical properties based on the output of CROCUS and estimates the snow cover stability.

The main difference between the snow cover models is the scale over which they are operating. SNOWPACK, driven by weather station data, simulates the local snow cover at the location of the automatic weather station. The French model chain simulates the snow cover for so-called massifs covering about 500 km^2. Model results are represented on so-called virtual pyramids, i.e., 300 m elevation bands on 6 aspects each.

Only a few studies on snow cover modelling in Canada have been carried out throughout the last years. Mingo and McClung (1998) used the snow cover model CROCUS to simulate the snow cover of two different snow climates in western Canada. They found the simulations in good agreement with the observations in regard to snow depth, snow temperature and density. They pointed out that the simulations with CROCUS, especially the metamorphic processes are sensitive to the climate regions and adjustments are required. Furthermore, they showed the potential of CROCUS to simulate critical snow layers such as surface hoar and crusts.

Smith et al. (2008) assessed the capability of the snow cover model SNOWPACK to model the formation and evolution of a melt-freeze crust formed in the Columbia Mountains of British Columbia, Canada. They found a poor performance of SNOWPACK regarding crust formation and evolution, but pointed out the sensitivity of snow cover models to their input data.

In this study we present the first initial attempt of coupling the snow cover model SNOWPACK with the Canadian weather forecasting model GEM15 to the model chain pSNOWPACK. In a first step we compare the forecasted precipitation amounts with the measured values to (a) assess the accuracy of the forecast in mountainous terrain and

(b) to derive possibly required filtering methods. Finally, we assess the capability of the model chain pSNOWPACK to simulate snow depth, new snow amounts as well as surface hoar and crust formation at a study plot located in the Columbia Mountains of British Columbia, Canada.

2 Data

For this study we analysed precipitation data as well as manual observations from Mt. Fidelity, Rogers Pass, British Columbia, Canada (Fig. 1). The study plot is located at 1905 m a.s.l. at tree line in a transitional snow climate with a strong maritime influence (Hägeli and McClung, 2003). We analysed data from October to May of five winters between 2005 and 2010.

Precipitation was measured with a precipitation gauge and recorded hourly. The precipitation gauge has an accuracy of 1 mm, i.e. precipitation events of less than one millimetre were not captured reliably.

The new snow amounts were derived from hourly snow height measurements with an ultra-sonic sensor above a storm-board at Mt. Fidelity Study Plot. The snow cover model SNOWPACK provides for each time-step a 24-h new snow value, i.e. a conventional 24-h snow board reading HN(24 h). For comparison of observed and simulated daily new snow amounts we compared the measured and simulated values at midnight for each day. The new snow was removed most days from the snow board at Mt. Fidelity Study Plot. In this case the reading prior to clearing was added to the measured value at midnight. Due to ongoing snow settlement, this procedure does not perfectly reproduce a manual measurement of HN(24 h). Nevertheless we consider it to be a very good approximation of the real value. The total snow depth at Mt. Fidelity was manually measured most days with an accuracy of ±1 cm.

The Canadian Meteorological Centre (CMC) in Montreal provided forecasted values of the regional model GEM15 for the five winters between 2005 and 2010. These data were used as input for the snow cover model SNOWPACK as well as for validation of the forecast.

Manual snow profiles were used for comparison with the simulated stratigraphy with a focus on surface hoar and melt-freeze crust formation.

3 Methods

3.1 The regional numerical weather model GEM15

The short-range weather forecast issued by the Canadian Meteorological Centre (CMC) is based on the Global Environmental Multiscale model (GEM, Côté et al., 1998a, 1998b). In 2004 a new version (GEM15, Mailhot et al., 2005) became operational with a higher horizontal and vertical resolution; 15 km and 58 atmospheric levels instead of 24 km and 28 levels. In addition to the increase in resolution, the model physics was improved (for more details see Mailhot et al., 2005).

GEM15 provides a forecast up to 48-h and is initiated twice a day at 00:00 UTC and 12:00 UTC (UTC, Coordinated Universal Time). Forecasted values are available every 3-h after initiation. For this study the forecasted values for hours 3, 6, 9 and 12 after each initiation where used to create a time series with 3-h time-steps. The 12-h forecasting steps after initiation at 00:00 UTC and 12:00 UTC were assigned to noon and midnight, respectively. The observation time was transformed from Pacific Standard Time (PST) to Coordinated Universal Time (UTC).

We used data from the GEM15 grid-point ($n_i = 143$; $n_j = 122$) located at latitude 51.2339° and longitude −117.5898°. The elevation of the grid-point (1803 m a.s.l.) is lower than the elevation of the study plot (1905 m a.s.l). Therefore the forecasted air temperature was adjusted accordingly by a dry-adiabatic lapse rate of −1 °C per 100 m. All other forecasted values except for the precipitation amounts (see details below) remained unfiltered.

A 3-h sum of the precipitation amounts as measured at Mt. Fidelity by the precipitation gauge was calculated to allow a comparison with the forecasted precipitation amounts.

3.2 The snow cover model SNOWPACK

The Swiss snow cover model SNOWPACK was used to simulate the snow cover using GEM15 forecasted values as input data. Many changes to the source code have been made since 2002 and only some of them have been published. The following summarizes the main SNOWPACK setup used for this study.

Snow cover simulations were performed with SNOWPACK release SnowpackR_20110801. The output time-step was set to 180 min to match the 3-h steps of GEM15. SNOWPACK can be run with various combinations of meteorological input values. For this study SNOWPACK was driven using the incoming short and long-wave radiation, the amount of precipitation, air temperature and relative humidity, wind speed and direction, all of them forecasted values of GEM15. SNOWPACK was initialized with no snow on the ground on 1 October 2009. Note that forecasted data only are used throughout a simulation with no attempt whatsoever to optimize input with measured values.

In spring 2011 a new settlement routine (unpublished) was implemented and used for this study. The parameterization proposed by Lehning et al. (2002b) was used to estimate the initial new snow density from air and surface temperature as well as wind speed and relative humidity. Here "initial" means that the calculated density corresponds to snow deposited within the last hour. The parameterization was slightly modified to keep new snow densities below 90 $\mathrm{kg\,m^{-3}}$ for air temperatures below $-10\,^{\circ}\mathrm{C}$.

Atmospheric conditions were considered to be neutral. The energy exchange at the snow surface was calculated using Neuman boundary conditions. To compare the simulated and measured snow depth at Mt. Fidelity Study Plot a daily average was calculated from the simulations with SNOWPACK.

3.3 Filtering methods

To assess the capability of GEM15 to forecast the correct amount of precipitation the ratio of observed to forecasted amount was considered for each time-step:

$$R = \log_{10}\left(\frac{P_{\mathrm{GEM}}}{P_{\mathrm{OBS}}}\right) \tag{1}$$

with P_{GEM} as the forecasted precipitation amount and P_{OBS} the observed amount. Negative values would indicate under-estimation and positive values over-estimation of precipitation amounts.

In addition, we calculated the difference (D) in precipitation amounts in mm for each time step:

$$D = P_{\mathrm{GEM}} - P_{\mathrm{OBS}} \tag{2}$$

Negative values will indicate too little and positive too much forecasted precipitation.

Only precipitation events where P_{GEM} was larger 1 mm were considered for calculating the correction factors per time-step. For further analysis precipitation classes with a 1 mm increment starting from 0 mm were defined.

4 Results

4.1 Verification of forecasted precipitation amounts

The distributions of the correction factors of four winters between 2005 and 2009 derived by Eqs. (1 and 2) per GEM15 precipitation class are shown in Fig. 2. The median $\bar{R}$ for each class were observed to be positive, i.e. an over-estimation, for all precipitation classes larger than 1 mm (Fig. 2a). This is consistent with the median correction factors $\bar{D}$ being positive for all precipitation classes (Fig. 2b). However, with smaller precipitation events (<3 mm), GEM15 often under-estimates the precipitation amounts.

4.2 Filtering of forecasted precipitation amounts

We estimated the systematic over-estimation shown in Fig. 2a and b by fitting a logarithmic and linear model to the median $\bar{R}$ and $\bar{D}$, respectively, of each precipitation class (solid lines in Fig. 2). The logarithmic model is defined by:

$$\bar{R} = a + b \log_{10}(P_{\mathrm{CLASS}}) \tag{3}$$

with P_{CLASS} the GEM15 precipitation class in mm and coefficients $a = 3.6 \times 10^{-5}$ and $b = 0.39$. The best linear fit was obtained by:

$$\bar{D} = c + d\,P_{\mathrm{CLASS}} \tag{4}$$

with coefficients $c = -0.52$ mm and $d = 0.70$. Only data from the four winters between 2005 and 2009 were used for model fitting. The winter 2009–2010 was used for validation of the filtering methods only.

The forecasted precipitation amounts were filtered by (a) dividing the forecasted precipitation amounts with the correction factor $10^{\bar{R}}$ derived from Eq. (3) (ratio method) or (b) subtracting the correction factor calculated from Eq. (4) from the forecasted values (difference method) and finally c) by dividing all forecasted precipitation amounts with a constant factor (constant method). Here we take the median R^* of $\log_{10}(\mathrm{P_{GEM}}/\mathrm{P_{OBS}})$ of all precipitation events larger 1 mm for the four winters and transform it to

$$C = 10^{R^*} = 10^{0.12} = 1.32. \tag{5}$$

Summary statistics for observed, unfiltered and filtered precipitation amounts for the winter season of 2009–2010 are shown in Table 1. The total amount of precipitation for events larger than 1 mm measured with the precipitation gauge at Mt. Fidelity Study Plot was 1052 mm. GEM15 forecasted 1528 mm for the same period. The ratio method shows the best results regarding the total amount of precipitation (1081 mm). However, the maximum amount of precipitation for this filtering method is about a factor of 3 smaller than observed indicating an over-correction of large precipitation events.

4.3 Verification of simulated snow depth and new snow amounts

The snow cover was simulated at Mt. Fidelity Study Plot for the winter 2009–2010 using GEM15 forecasted values as input. The measured snow depth was compared to the SNOWPACK simulations using unfiltered and filtered precipitations amounts as input (Fig. 3). The simulated snow depth using the unfiltered GEM15 precipitation amounts consistently over-estimates the snow depth through the entire winter season. Simulations with the filtered data over-estimate the snow depth for the early season (Oct–Nov) and tend to under-estimate the snow depth during the mid season (Nov–Feb). The simulation with precipitation amounts filtered by the difference method tends to over-estimate the snow depth for the late season (Feb–May), whereas the simulations with filtered values using either the ratio method or the constant method are in good alignment with the observations for the same period.

The difference between simulated and measured snow depths are shown in Fig. 4. Negative values indicate under-estimation and positive values indicate over-estimated snow depth. The constant method shows the smallest median deviation from zero compared to the unfiltered data and the other two filtering methods. The first and third quartiles, i.e. 50 % of the data, are within a range of about ±10 cm. Nevertheless, negative outliers of about 40 cm also exist for this method.

The simulated and measured 24-h new snow amounts HN(24 h) are compared in Fig. 5. The median difference between the simulation and observation is positive, i.e. an over-estimation, for simulations with unfiltered as well as with filtered precipitation amounts. Beside some outliers SNOWPACK reproduces the new snow amounts for simulations with unfiltered and filtered precipitation with an accuracy of about ±10 cm in a little less than 75 % of the cases. The filtering methods tend to reduce the number of positive outliers (over-estimation), but also produce larger negative outliers (under-estimation).

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4.4 Surface hoar and crust formation

The flat field 2009–2010 simulation for Mt. Fidelity Study Plot is shown from December 2009 to April 2010 in Fig. 6. The manual snow profile from Mt. Fidelity (20 March 2010) as well as the simulated profile for the same date are shown in Fig. 7. Only one manual flat field profile (20 March 2010) was available for comparison with the simulation for Mt. Fidelity Study Plot. In total, two melt-freeze crusts and four surface hoar layers were observed on 20 March 2010 at Mt. Fidelity Study Plot. All surface hoar layers (purple lines) but one were modeled by SNOWPACK. The upper observed melt-freeze crust was not modeled, whereas the lower crust at about 30 cm was reproduced by SNOWPACK (red-blue line).

5 Discussion

Snow cover models are strongly dependent on their input data. That means a model can only be as good as the input data. One of the most critical parameter for snow cover modelling is the precipitation amount. However, precipitation is among the most difficult parameters to be forecast by numerical weather predictions models. Even high-resolution recent model developments therefore show considerable scatter and biases (e.g. Weusthoff et al., 2010). Precipitation processes triggered or modified by orography are most challenging. Numerical weather prediction models tend to over-estimate the precipitation amounts on the upwind side and under-estimate the precipitation amounts on the downwind side. The consistent over-estimation of precipitation shown in Fig. 2a and b can partly be explained by this effect since the GEM15 grid-point is located on the up-wind side, west of Rogers Pass (Fig. 1). After filtering the forecasted precipitation amounts with the ratio method and constant method the forecasted precipitation amounts are mostly in good alignment with the observations. However, some of the large precipitation events are over-corrected with the ratio method at least for the winter season of 2009–2010. In addition, GEM15 tends to under-estimate the precipitation amounts of small precipitation events. No method for filtering these events was attempted in this initial study. Some of these under-estimated events might also be related to poor timing of precipitation events. Taking adjacent grid-points into account might help to improve the filtering for under-estimated small precipitation events. In addition, more advanced filtering methods, e.g. Kalman filtering, could be applied for regions where precipitation amounts are measured.

The knowledge about the exact snow depth is secondary for avalanche warning services. Avalanche warning services are more interested in the snow cover layering and the formation and evolution of critical layers. However, for hydrological purposes it is of particular interest how much snow – or more precisely, how much snow water equivalent (SWE) – is available within an alpine catchment especially when snow melting starts. Nevertheless for avalanche forecasting, the snow depth needs to be modeled with some confidence since the depth of critical layers such as surface hoar layers and crusts is required for assessing the propensity of human-triggered slab avalanches (e.g. Schweizer et al., 2003). The simulations of the snow depth with the snow cover model SNOWPACK (Fig. 3) showed again good results for the ratio and constant filtering method, where the constant method tends to show the smallest overall deviation from the observations (Fig. 4). The early season over-estimation of snow depth can be explained by the fact that SNOWPACK treated precipitation as snow only instead of rain or mixture of rain and snow. The snow cover model SNOWPACK uses an adjustable threshold for the air temperature T_a set by default to 1.2 °C to distinguish if precipitation is treated as rain ($T_a >= 1.2\,^{\circ}\mathrm{C}$) or snow ($T_a < 1.2\,^{\circ}\mathrm{C}$). However, atmospheric conditions can sometimes cause rain with subfreezing air temperature and snow can fall sometimes heavily with positive air temperature. More research is required to assess whether an analysis of the vertical layering, forecasted by GEM15, can be used to address this issue. The difference method cannot be used for filtering precipitation amounts, because it filters all large events and it is therefore not appropriate since these events are of particular interest for avalanche warning services.

The expected new snow amounts for the next day are valuable information for avalanche warning services in their assessment of the avalanche danger. Therefore we compared the forecasted and observed 24-h new snow amounts at Mt. Fidelity Study Plot (Fig. 5). The simulations with unfiltered and filtered precipitation amounts tend to over-estimate the 24-h new snow amounts, but in most of the cases the accuracy is within a range of ±10 cm. However, a few outliers exist on both sides. All positive outliers, i.e. over-estimation, are related to the early season over-estimation of the snow depth induced by SNOWPACK producing too much snow instead of rain as mentioned above. The negative outliers, i.e. an under-estimation, are mostly related to large storm events with low-density snow (density HN(24 h) $<50\,\mathrm{kg\,m^{-3}}$). Summary statistics for a snowfall event in January 2010 are shown in Table 2. On 15 January, 30 mm of precipitation were measured at Mt. Fidelity Study Plot resulting in about 52 cm of new snow over 24-h. This corresponds to a 24-h snow density of about $50\,\mathrm{kg\,m^{-3}}$ However, since the HN(24 h) measurement includes settlement the actual new snow density during the storm can assumed to be smaller than $50\,\mathrm{kg\,m^{-3}}$. Although, GEM15 forecasted only 5 mm less precipitation for this day than observed, 20 cm less snow over 24-h was modelled (Table 2). SNOWPACK estimates the new snow density with an empirical model based on meteorological and snow surface parameters. This statistical model was derived from observations at Weissfluhjoch study plot located above Davos (Switzerland) in a transitional or intermountain climate. The set contained not many data for low-density snow and air temperatures above roughly −10 °C. That means snowfall events with low-density snow, as regularly observed in the Columbian Mountains, cannot be simulated correctly by SNOWPACK resulting in an under-estimation of these events. The new snow density calculated with SNOWPACK for the 15 January snowstorm as well as the corresponding observed and forecasted precipitation amounts are shown in Fig. 8. The modelled 24-h new snow density for midnight on 15 January was $72\,\mathrm{kg\,m^{-3}}$ (Table 2), i.e. even with the correct amount of forecasted precipitation, SNOWPACK will not be able to produce the correct amount of new snow. Furthermore, the filtering methods further reduced the precipitation amounts resulting in a even larger deviation from the observed HN(24h). A new dataset including low-density snow events would substantially improve the ability of SNOWPACK to simulate these events correctly.

The most important information for avalanche warning services is information about the snow cover stratigraphy. Various active surface hoar layers in the upper snow cover dominated the winter season of 2009–2010 in the Columbian Mountains. By 20 March 2010 four surface hoar layers were observed within the snow cover at Mt. Fidelity Study Plot (Fig. 7). All surface hoar layers but one were modelled by SNOWPACK. Buried melt-freeze crusts favour faceting, i.e. the formation of a weak layer, and the adjacent layers are often less bonded to the crust forming a critical interface (Jamieson, 2006). Only one of the two observed crusts was modelled by SNOWPACK. The thick simulated basal crust was formed early season when a single large precipitation event was treated by the model as rain instead of snow. The lower part of the snow cover was observed to be more faceted than the upper part, which was dominated by small rounded grains. This general structure was also simulated by SNOWPACK. In summary, the simulated profile is in good agreement with the observation as SNOWPACK reproduced most of the critical layers and the overall layering well.

6 Conclusions

We showed the first initial attempt of coupling the snow cover model SNOWPACK with the numerical weather prediction model GEM15 to form the model chain pSNOWPACK. Filtering the forecasted precipitation amounts became necessary since GEM15 tended to over-estimate the precipitation amounts (Fig. 2). Three different filtering methods were suggested for pre-processing the GEM15 forecasted precipitation amounts. Applying a constant factor of 1.32 to the forecasted amounts provides the best results if covering the larger precipitation events is considered to be more relevant than the total amounts (Table 1). After filtering the input data for SNOWPACK the simulated snow depth is in good alignment with the observations for the winter 2009–2010 at Mt. Fidelity Study Plot. The 24-h new snow amounts were reproduced with an accuracy of

±10 cm for almost 75 % of the 3-h periods. However, an under-estimation of new-snow amounts especially for large storms with low-density snow remains for a few cases. Most of the critical layers as well as the general stratigraphy were well modelled by SNOWPACK.

In conclusion, the model chain pSNOWPACK shows promising potential as a practical forecasting tool for avalanche warning services especially for areas where snow cover observations are rare.

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Table 1. Summary statistics for measured (Obs.), forecasted (GEM) and filtered precipitation amounts with three different methods (see text) for the winter 2009–2010 at Mt. Fidelity study plot. Given are the minimum and maximum (Min., Max.), the mean and median (Mean, Median), the first and third quartile (Q1, Q3) as well the total amount of precipitation (Sum).

	Obs.	GEM	RATIO	DIFF	CONST
	mm	mm	mm	mm	mm
Min.	0	0	0	0.5	0
Q_1	0	0	0	0.5	0
Median	0	0.3	0.3	0.6	0.2
Mean	0.6	0.9	0.6	0.8	0.7
Q_3	1.1	1.0	1.0	0.8	0.8
Max.	14.7	16.4	5.6	5.4	12.5
Sum	1052	1528	1081	1336	1157

Table 2. Summary statistics for a snowfall event that occurred between 14 January 2010 and 16 January 2010 at Mt. Fidelity Study Plot, Rogers Pass BC, Canada. Shown are for each day the observed (Obs.) and simulated unfiltered (pSNP) 24-h values of the new snow amounts at midnight (HN), the corresponding precipitation amounts (P) and the resulting 24-h new snow densities (ρ_{HN}).

Date	HN		P		ρ_{HN}	
	Obs. cm	pSNP cm	Obs. mm	pSNP mm	Obs. kg m^{-3}	pSNP kg m^{-3}
14 January	7.8	16.3	6.4	12.0	75.2	67.5
15 January	52.3	32.3	30.4	25.5	53.3	72.4
16 January	25.9	23.7	12.5	16.9	44.3	65.4

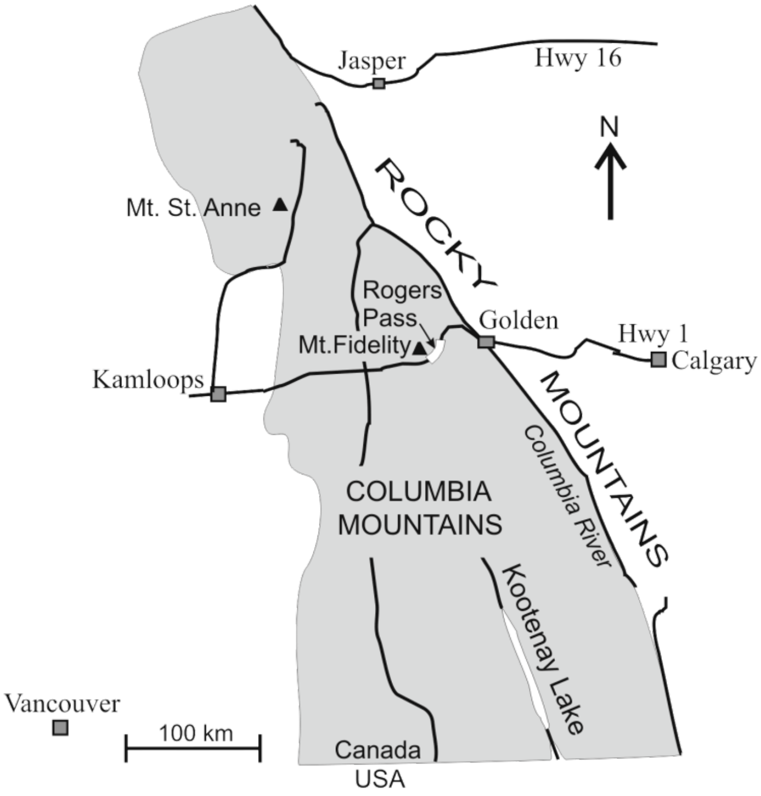

Fig. 1. Map of the Columbia Mountains, British Columbia, Western Canada. Mt. Fidelity Study Plot is located at 1905 m a.s.l., west of Golden, close to Rogers Pass (Trans-Canada Highway 1).

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Interactive Discussion

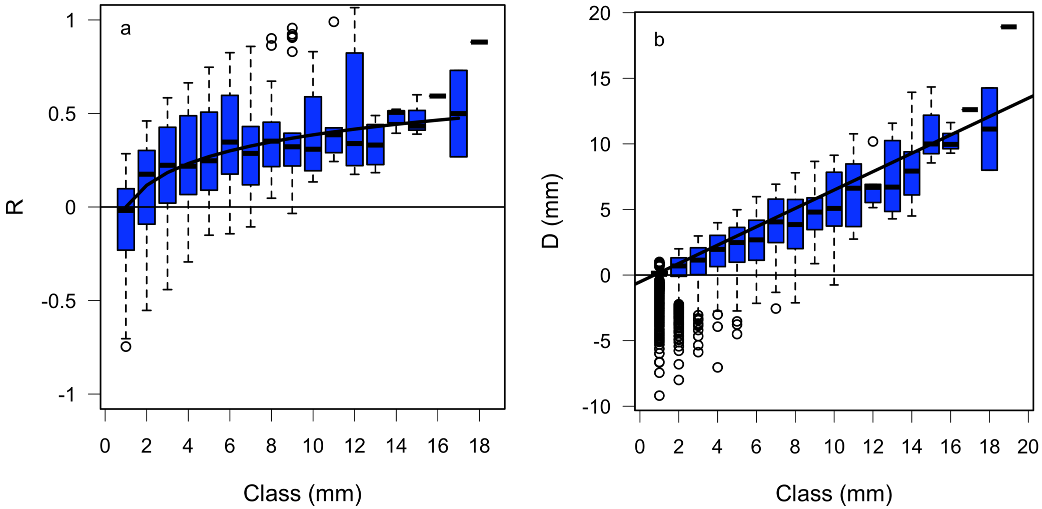

Fig. 2. Correction factors per precipitation class for **(a)** *R* (Eq. 1), and **(b)** D (Eq. 2). Solid lines show a logarithmic fit (R) and a linear fit (D). The median R^* calculated by Eq. (1) over four winters was 0.12 or 1.32, respectively (compare Eq. (5). Boxes span the interquartile range. Whiskers extend to 1.5 times the interquartile range. Open circles indicate outliers.

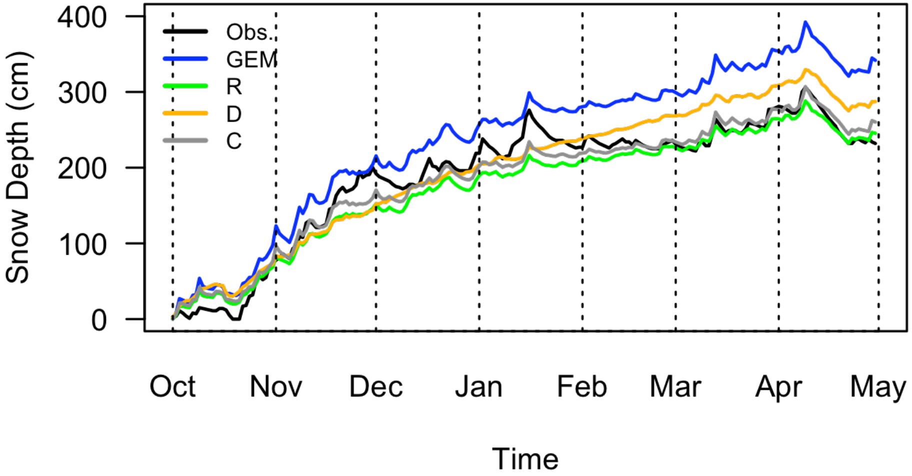

Fig. 3. Comparison of observed and simulated snow depths at Mt. Fidelity Study Plot for the winter 2009–2010. The black solid line shows the daily manually measured snow depth. The remaining lines show simulated snow depths with unfiltered precipitation values (blue solid line) and filtered precipitation using ratio method R (green), difference method D (orange) and constant method C (grey).

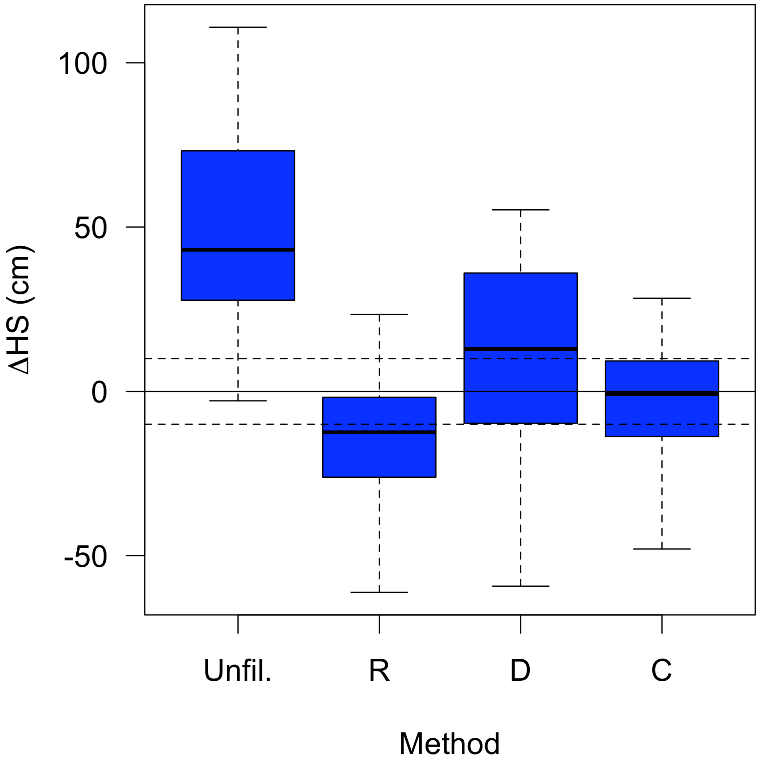

Fig. 4. Difference between measured and simulated snow depth with unfiltered and filtered precipitation amounts as input data. Unfiltered (Unfil.), ratio method (R), difference method (D) and constant method (C). Dashed lines are located at ±10 cm. Boxes, whiskers and open circles as in Fig. 2.

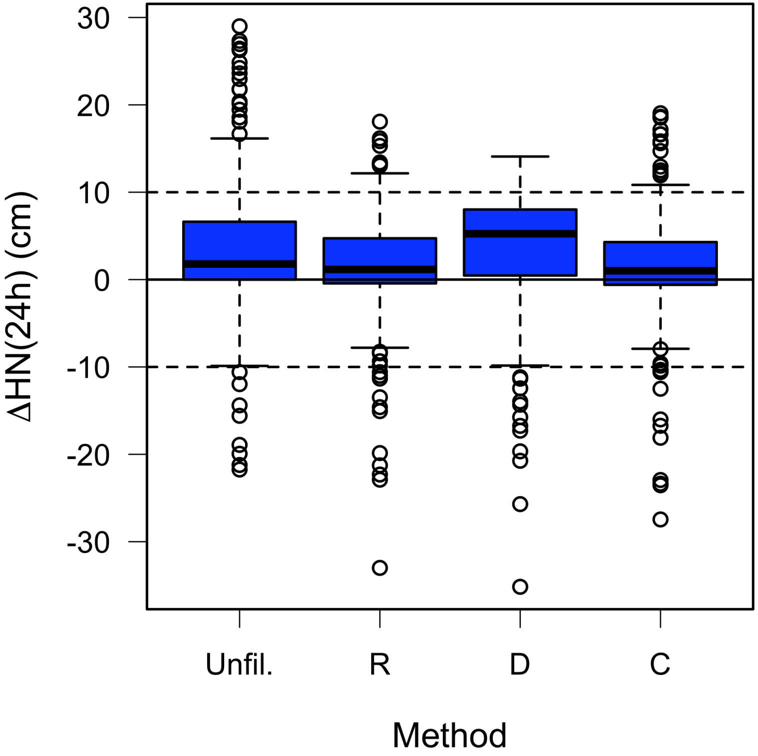

Fig. 5. Difference between measured and simulated 24-h new snow amounts ΔHN(24 h) for the winter 2009–2010 at Mt. Fidelity Study Plot. Shown are the differences for the simulation with unfiltered (Unfil.) and filtered precipitations amounts using ratio method (R), difference method (D) and constant method (C). Boxes, whiskers and open circles as in Fig. 2. Dashed lines are located at ±10 cm.

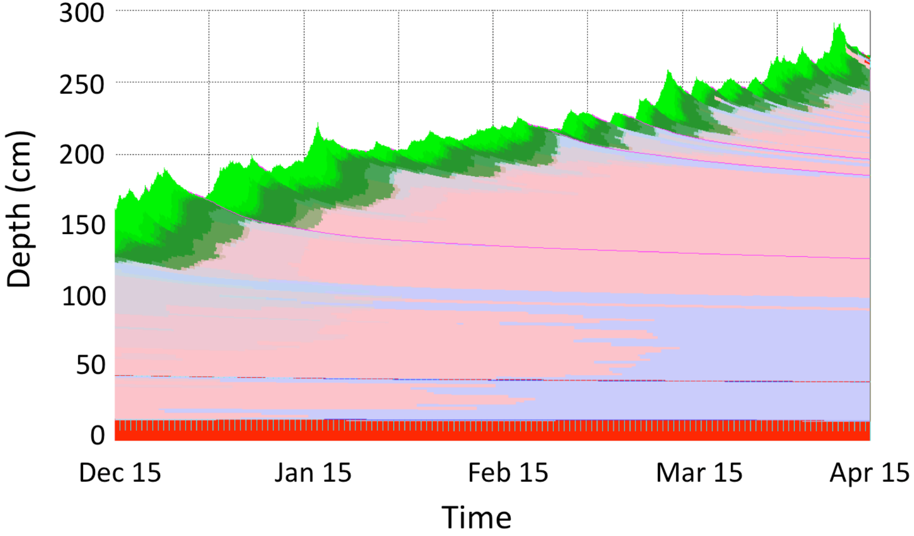

Fig. 6. Snow cover simulation with the snow cover model SNOWPACK for the winter 2009–2010 at Mt. Fidelity Study Plot, Rogers Pass, BC, Canada. Colors represent different grain types (green: precipitation, particles, light pink: rounded grains, blue: faceted crystals, red: melt forms). Purple lines indicate surface hoar layers and hatched layers melt-freeze crusts (upper base and at 50 cm).

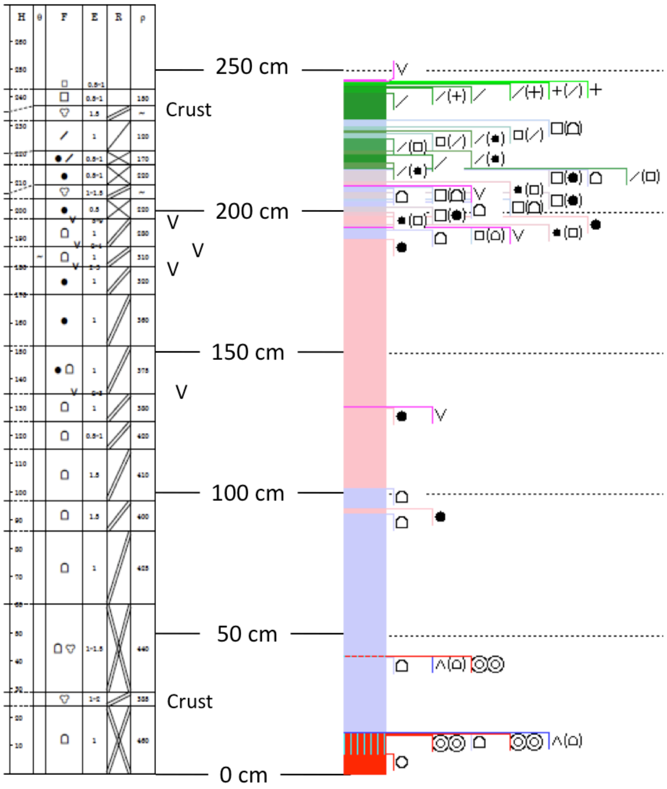

Fig. 7. Observed manual flat field profile (left) and simulated profile (right) for 20 March, 2010 at Mt. Fidelity Study Plot. Snow symbols according to Fierz et al. (2009).

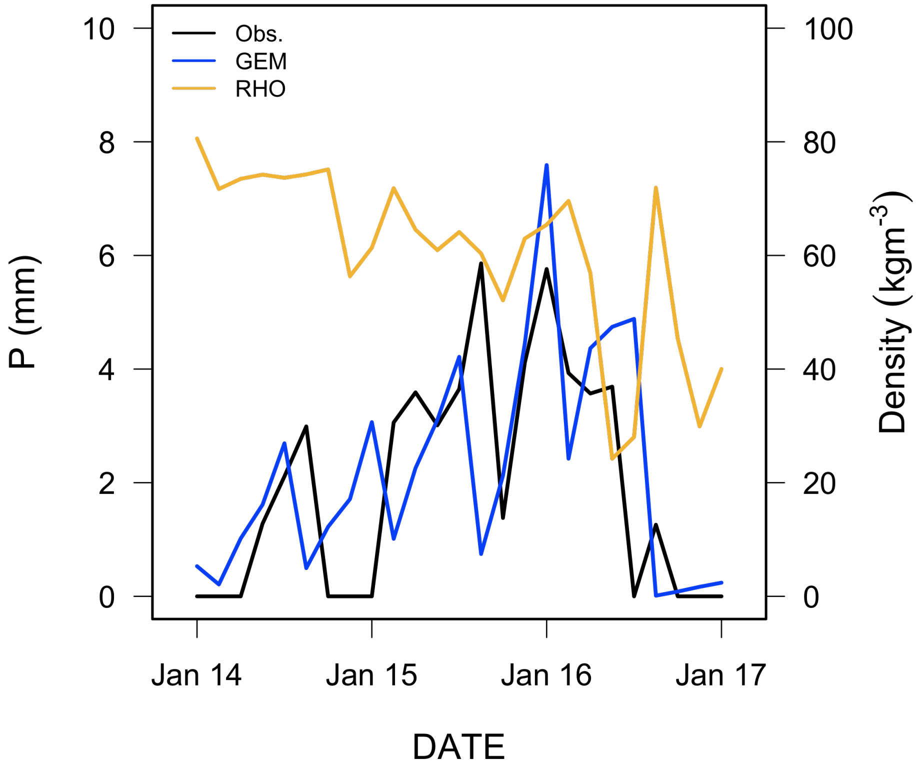

Fig. 8. Observed (Obs.) and forecasted (GEM) 3-h precipitation amounts as well as the modeled initial new snow density (RHO) for the period of January 14 to 16 January, 2010 at Mt. Fidelity Study Plot. Values located at the tick marks correspond to the midnight values.