Forcing the snow-cover model SNOWPACK with forecasted weather data

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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. The output of GEM15 was compared to meteorological as well as snow cover data from Mt. Fidelity, British Columbia, Canada, for five winters between 2005 and 2010. Precipitation amounts are most difficult to predict for weather forecasting models. Therefore, we first assess the capability of the model chain to forecast new snow amounts and consequently snow depth. 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 and new snow events were well modelled. In a case study two key factors of snow cover instability, i.e. surface hoar formation and crust formation were investigated at a single point. Over half of the relevant critical layers were reproduced. Overall, the model chain shows promising potential as a future forecasting tool for avalanche warning services in Canadian data sparse areas and could thus well be applied to similarly large regions elsewhere. However, a more detailed analysis of the simulated snow cover structure is still required.

Keywords: SNOWPACK, numerical weather predictions, GEM15, snow cover modelling, avalanche forecasting, numerical weather models

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. For very large forecasting regions this might result in little or no information on the state of the snow cover in some areas.

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 data from about 250 automatic weather stations (AWS). 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 1 345 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 exist 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 on a regular basis, making the now-cast and the forecast impossible, at best a report based on the sparse available information can be issued.

Snow cover models are becoming 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, 2002b; 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 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 operate. 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 of a single crust, 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. In a first step we compare the forecasted meteorological parameter 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 to simulate snow depth, new snow amounts and provide a case study of 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 meteorological data as well as manual observations from Mt. Fidelity, Rogers Pass, British Columbia, Canada (Figure 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-hour new snow value, i.e. a conventional 24-hour snow board reading HN(24h). 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(24h). Nevertheless we consider it to be a reasonable approximation of the real value. The total snow depth at Mt. Fidelity was manually measured most days with an accuracy of ± 1 cm.

Incoming short and long-wave radiation as well as air temperature and relative humidity were measured every 30 minutes at Mt. Fidelity study plot.

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-hours and is initiated at 00 UTC and 12 UTC (UTC, Coordinated Universal Time). Forecasted values are available in 3-hour steps 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-hour time-steps. The 12-hour forecasting steps after initiation at 00 UTC and 12 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°, 5.7 km West of Mt. Fidelity Study Plot. 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-hour 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. For all other parameters, i.e. radiation, air temperature and relative humidity, a 3-hour average was calculated.

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 minutes to match the 3-hourly 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 were 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 kg m^{-3} for air temperatures below -10 °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:

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

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:

$$D = P_{GEM} - P_{OBS} \quad (2)$$

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 Eq. (1) and 2 per GEM15 precipitation class are shown in Figure 2. The median $\overline{R}$ for each class were observed to be positive, i.e. an over-estimation, for all precipitation classes larger than 1 mm (Figure 2a). This is consistent with the median correction factors $\overline{D}$ being positive for all precipitation classes (Figure 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 Figures 2a and 2b by fitting a logarithmic and linear model to the median $\overline{R}$ and $\overline{D}$, respectively, of each precipitation class (solid lines in Figure 2). The logarithmic model is defined by:

$$\overline{R} = a + b\log_{10}(P_{CLASS}) \quad (3)$$

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:

$$\overline{D} = c + d\,P_{CLASS} \quad (4)$$

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 $10^{\overline{R}}$ 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 $\log_{10}(P_{GEM}/P_{OBS})$ of all precipitation events larger 1 mm for the four winters and transform it to

$$C = 10^{R^*} = 10^{0.12} = 1.32. \quad (5)$$

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 3 smaller than observed indicating an over-correction of large precipitation events.

4.2 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 (Figure 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 Figure 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-hours new snow amounts HN(24h) are compared in Figure 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. Besides some outliers SNOWPACK reproduces the new snow amounts for simulations with unfiltered and filtered precipitation with an accuracy of about ± 10cm 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).

4.3 Verification of forecasted meteorological parameter

A comparison of forecasted and observed air temperature, relative humidity as well as incoming short wave and long wave radiation for five winters between 2005-2010 is shown in Figure 6. The median difference between the measured and forecasted air temperature was -1.9 °C, i.e. the model is too cold (Figure 6a). Correcting the forecasted air temperature for elevation difference results in an increase of the median difference to -2.9 °C. The comparison of the forecasted and measured relative humidity shows that the model is too dry (Figure 6b). A comparison of the incoming short wave radiation is shown in Figure 6c. The comparison only shows values larger than 50 W m^{-2} to reduce the effect of diffuse radiation and shading on the measured data, which are not considered by GEM15. The model tends to over-estimate the short wave radiation with a median difference of 43 W m^{-2}. The forecasted incoming long wave radiation is in good agreement with the observation, but tends to be slightly smaller (Figure 6d).

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 Figure 7. The manual snow profile from Mt. Fidelity (20 March 2010) as well as the simulated profile for the same date are shown in Figure 8. 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 parameters 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 recent developments of high-resolution models 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 Figures 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 (Figure 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 (Figure 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 (Figure 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. Three single precipitation events (Figure 9) occurring in October 2009 led to a total over-estimation of new snow amounts of about 60 cm. The observed settling on October 2nd and October 3rd (Figure 9) could be related to either the positive measured air temperature or rain. The two other events are more obvious since after clearing the board (rapid decrease of HN to zero) the new snow height measurement did not increase but precipitation was measured, i.e. it rained. The snow cover model SNOWPACK uses an adjustable threshold for the air temperature T_a set by default to 1.2 °C (dash-dotted line in Figure 9) to distinguish if precipitation is treated as rain ($T_a \geq 1.2$ °C) or snow ($T_a < 1.2$ °C). However, atmospheric conditions can sometimes cause rain with subfreezing air temperature and snow can fall sometimes heavily with positive air temperature. During the three events mentioned above the forecasted air temperature was below this threshold i.e. precipitation was treated as snow only. In addition, precipitation amounts were over-estimated resulting in a strong over-estimation of the simulated snow heights during the early season as shown in Figure 3. More research is required to assess whether an analysis of the vertical layering, forecasted by GEM15, can be used to address this issue.

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-hour new snow amounts at Mt. Fidelity Study Plot (Figure 5). The simulations with unfiltered and filtered precipitation amounts tend to over-estimate the 24-hour 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(24h) < 50 kg m^{-3}). 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.

Summary statistics for a snowfall event in January 2010 are shown in Table 2. On January 15, 30 mm of precipitation were measured at Mt. Fidelity Study Plot resulting in about 52 cm of new snow over 24-hours. This corresponds to a 24-hour snow density of about 50 kg m^{-3}. However, since the HN(24h) measurement includes settlement the actual new snow density during the storm can be assumed to be smaller than 50 kg m^{-3}. Although, GEM15 forecasted only 5 mm less precipitation for this day than observed, 20 cm less snow over 24-hours 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 dataset did not contain 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 Columbia Mountains, may not be simulated correctly by SNOWPACK resulting in an under-estimation of these events. The new snow density calculated with SNOWPACK for the January 15 snowstorm as well as the corresponding observed and forecasted precipitation amounts are shown in Figure 10. The modelled 24-hour new snow density for midnight on January 15 was 72 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.

A comparison of meteorological parameter relevant for snow cover evolution is shown in Figure 6. GEM15 tends to under-estimate the air temperature, i.e. the model is to cold. The model tends to over-estimate the incoming short wave radiation, which might be compensated by wind as well as the under-estimation of the air temperature. The incoming long wave radiation tends to be a bit lower compared to the measurements, but is in general good agreement with the measurements. The forecasted relative humidity is under-estimated by the model, which has an influence on the simulated surface hoar formation. More detailed analysis is required to investigate how the under-estimation of relative humidity affects surface hoar formation especially for the grain size. All these findings are in agreement with the findings of Mailhot et al. (2005). They investigated the model performance for winter and summer periods after GEM15 became operational.

Information about snow cover stratigraphy is important for avalanche warning services. Various active surface hoar layers in the upper snow cover dominated the winter season of 2009-2010 in the Columbia Mountains. By 20 March 2010 four surface hoar layers were observed within the snow cover at Mt. Fidelity Study Plot (Figure 8). All surface hoar layers but one were modelled by SNOWPACK. The simulated periods of surface hoar formation agree with the observation. 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 this time 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 reasonable agreement with the observation as SNOWPACK reproduced most of the critical layers and the overall layering well. However, more profiles need to be compared to the simulations especially for different aspects to validate the overall performance of the model chain.

6 Conclusions

We showed the first initial attempt of coupling the snow cover model SNOWPACK with the numerical weather prediction model GEM15. Filtering the forecasted precipitation amounts became necessary since GEM15 tended to over-estimate the precipitation amounts (Figure 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-hour new snow amounts were reproduced with an accuracy of ± 10 cm for almost 75% of the 3-hour 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 modelled by SNOWPACK using forecasted data as input. If filtering of other forecasted meteorological parameter would improve the performance of the model chain remains unknown.

In conclusion, this model chain shows promising potential as a practical forecasting tool for avalanche warning services especially for areas where snow cover observations are rare. However, a detailed verification of the simulated stratigraphy and stability on different aspects as well as elevation bands is required.

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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 (SNP) 24-hour values of the new snow amounts at midnight (HN), the corresponding precipitation amounts (P) and the resulting 24-hour new snow densities (ρ_{HN}).

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

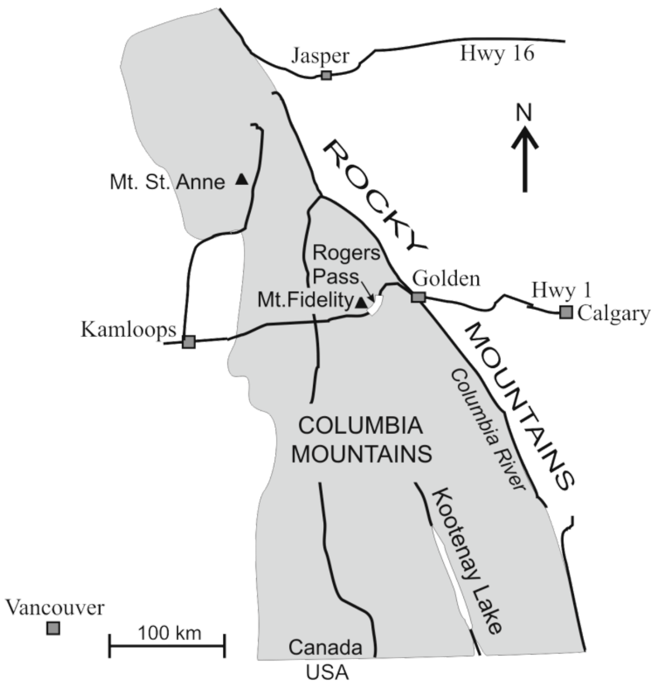


Figure 1: Map of the Columbia Mountains, British Columbia, Western Canada. Mt. Fidelity Study Plot is located at 1905 m a.s.l., west of Golden, close to Rogers Pass (Trans-Canada Highway 1).

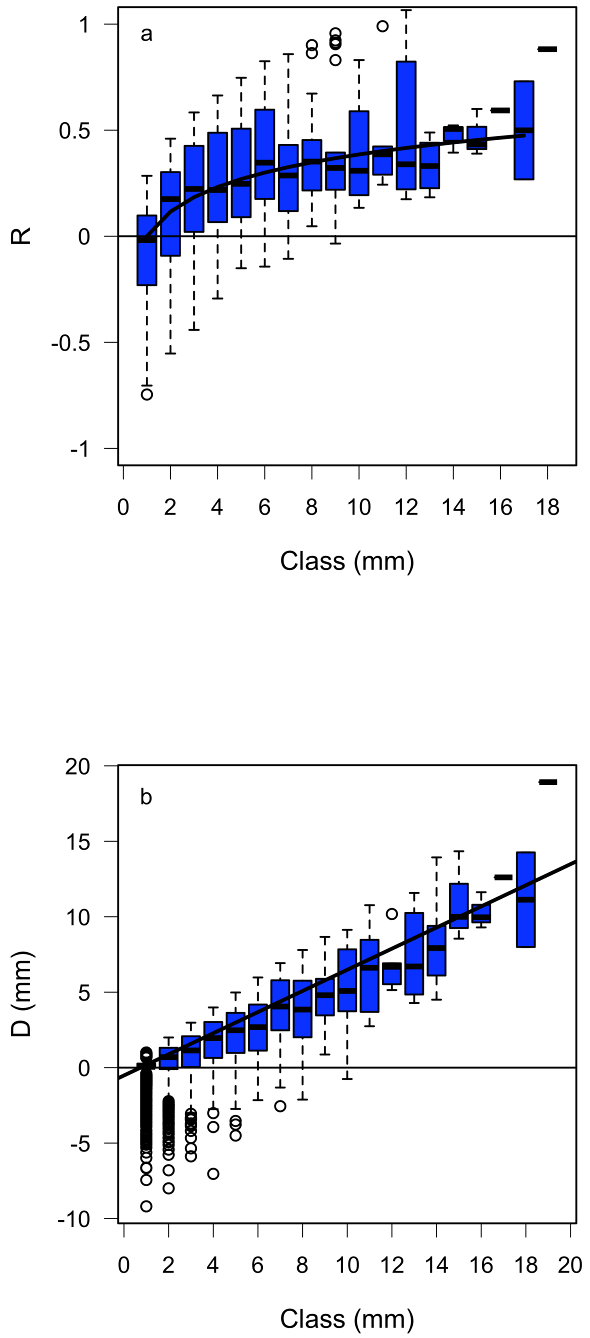


Figure 2: Correction factors per precipitation class for a) *R* (Eq. 1), and b) D (Eq. 2). Solid lines show a logarithmic fit (R) and a linear fit (D). The median R* calculated by Eq. (1) over four winters was 0.12 or 1.32, respectively (compare Eq. (5). Boxes span the interquartile range. Whiskers extend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

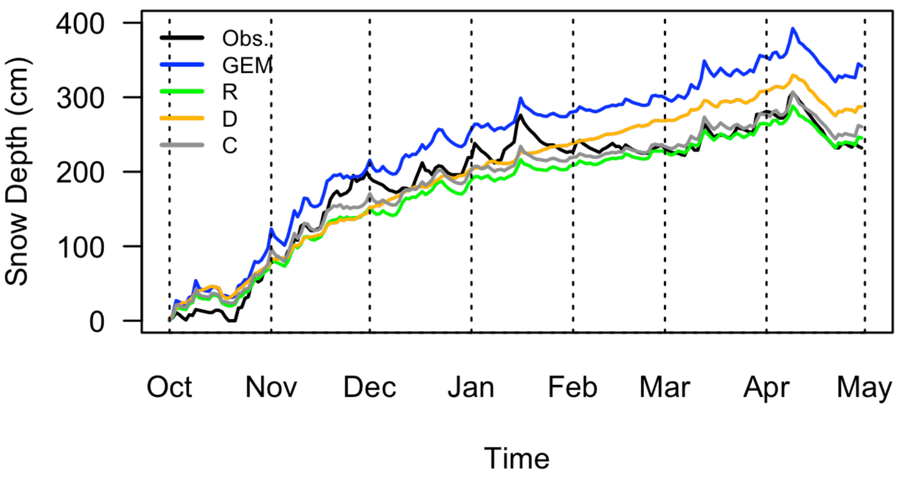


Figure 3: Comparison of observed and simulated snow depths at Mt. Fidelity Study Plot for the winter 2009-2010. The black solid line shows the daily manually measured snow depth. The remaining lines show simulated snow depths with unfiltered precipitation values (blue solid line) and filtered precipitation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

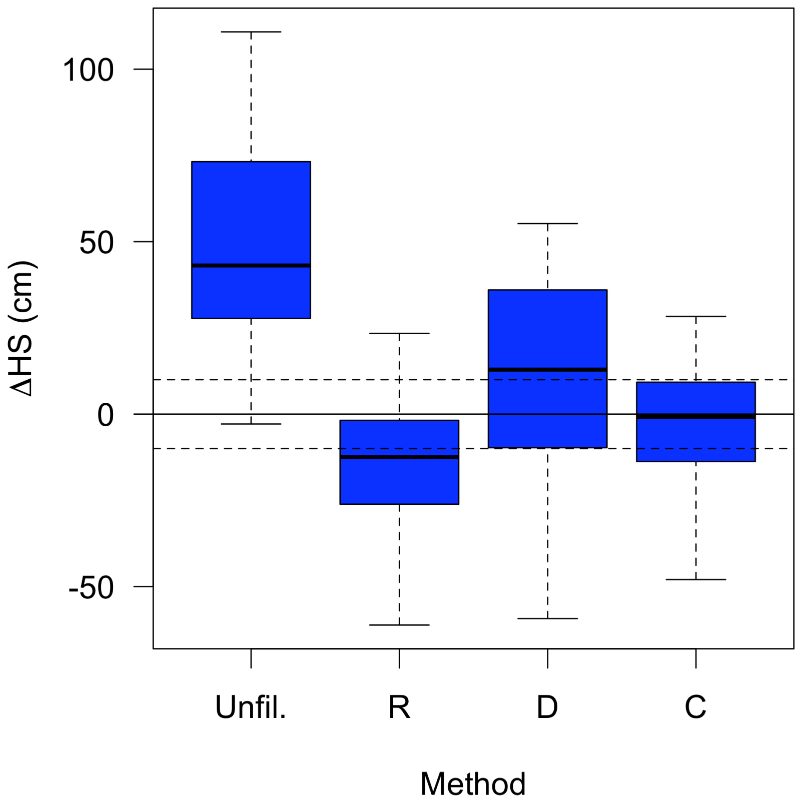


Figure 4: Difference between measured and simulated snow depth with unfiltered and filtered precipitation amounts as input data. Unfiltered (Unfil.), ratio method (R), difference method (D) and constant method (C). Dashed lines are located at ± 10 cm. Boxes, whiskers and open circles as in Fig. 2.

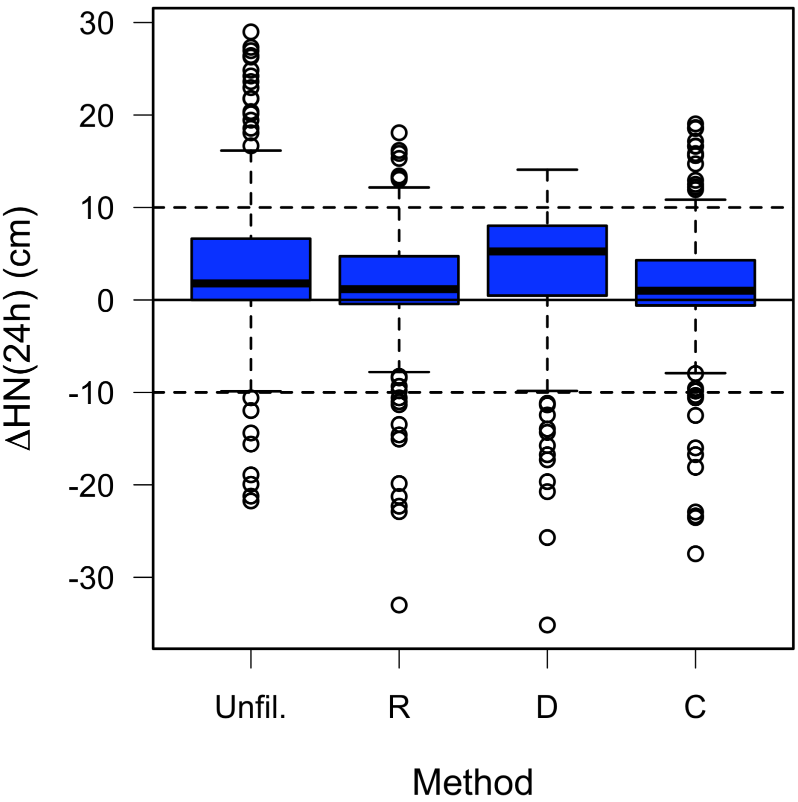


Figure 5: Difference between measured and simulated 24-hour new snow amounts ΔHN(24h) for the winter 2009-2010 at Mt. Fidelity Study Plot. Shown are the differences for the simulation with unfiltered (Unfil.) and filtered precipitations amounts using ratio method (R), difference method (D) and constant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

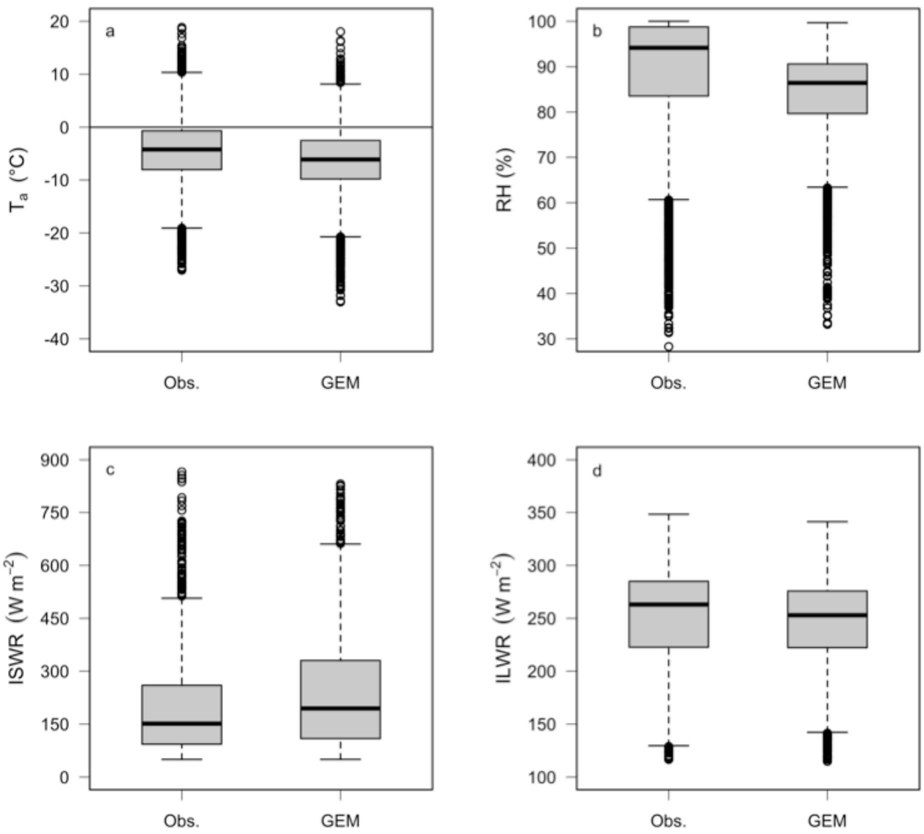


Figure 6: Comparison of important forecasted (GEM) and observed (Obs.) meteorological parameter. Shown are a) air temperature (°C), b) relative humidity (%) c) incoming short wave radiation (W m^{-2}) and d) incoming long wave radiation (W m^{-2}) for five winters between 2005 and 2010. For better comparison the incoming short wave radiation only shows values larger than 50 W m^{-2}.

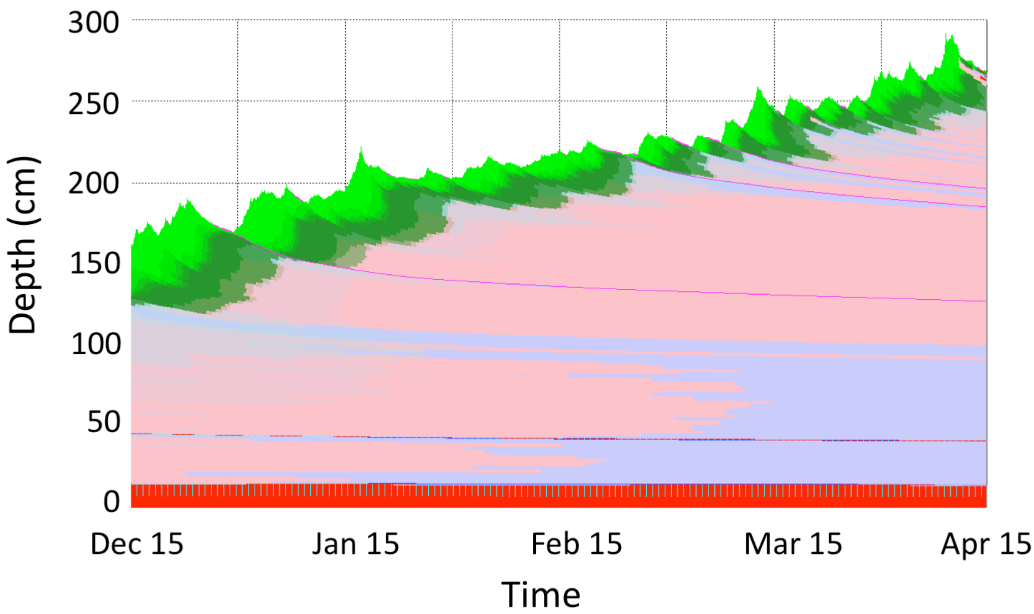
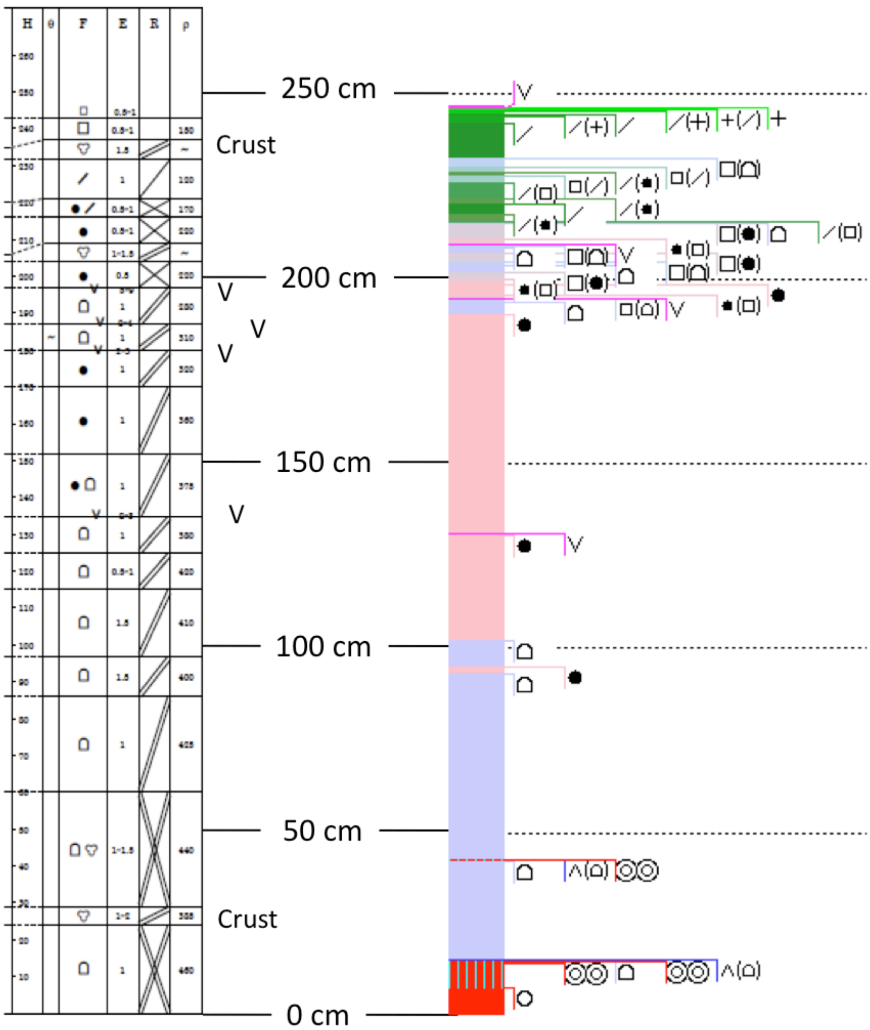
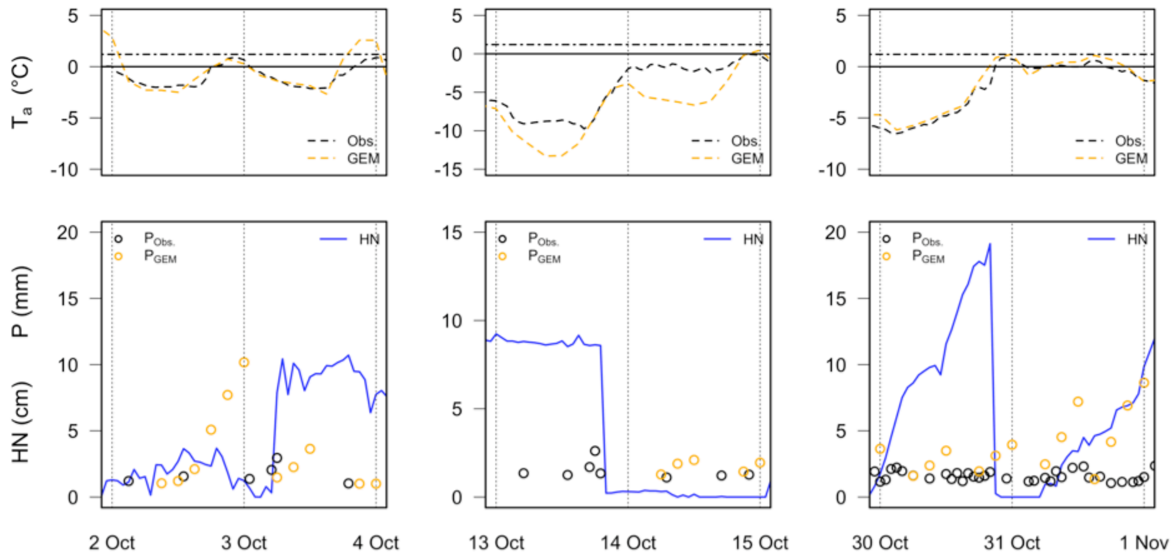


Figure 7: Snow cover simulation with the snow cover model SNOWPACK for the winter 2009-2010 at Mt. Fidelity Study Plot, Rogers Pass, BC, Canada. Colors represent different grain types (green: precipitation, particles, light pink: rounded grains, blue: faceted crystals, red: melt forms). Purple lines indicate surface hoar layers and hatched layers melt-freeze crusts (upper base and at 50 cm).



602 Figure 8: Observed manual flat field profile (left) and simulated profile
603 (right) for 20 March 2010 at Mt. Fidelity Study Plot. Snow symbols
604 according to Fierz et al. (2009).



605 Figure 9: Comparison of observed (Obs.) and forecasted (GEM) parameter for three precipitation events during October 2009 at Mt. Fidelity Study Plot. Upper graphs show a comparison of observed (Obs.) and forecasted (GEM) air temperature during these three events (same time scale as lower graphs). Horizontal dash-dotted line indicates the static 1.2 °C threshold used by SNOWPACK to distinguish between snow and rain. Lower graphs show the measured hourly precipitation amounts (black open circles, P > 1 mm) and the forecasted 3-hourly precipitation amounts (orange open circles, P > 1 mm) as well as the measured new snow amounts (blue solid line).

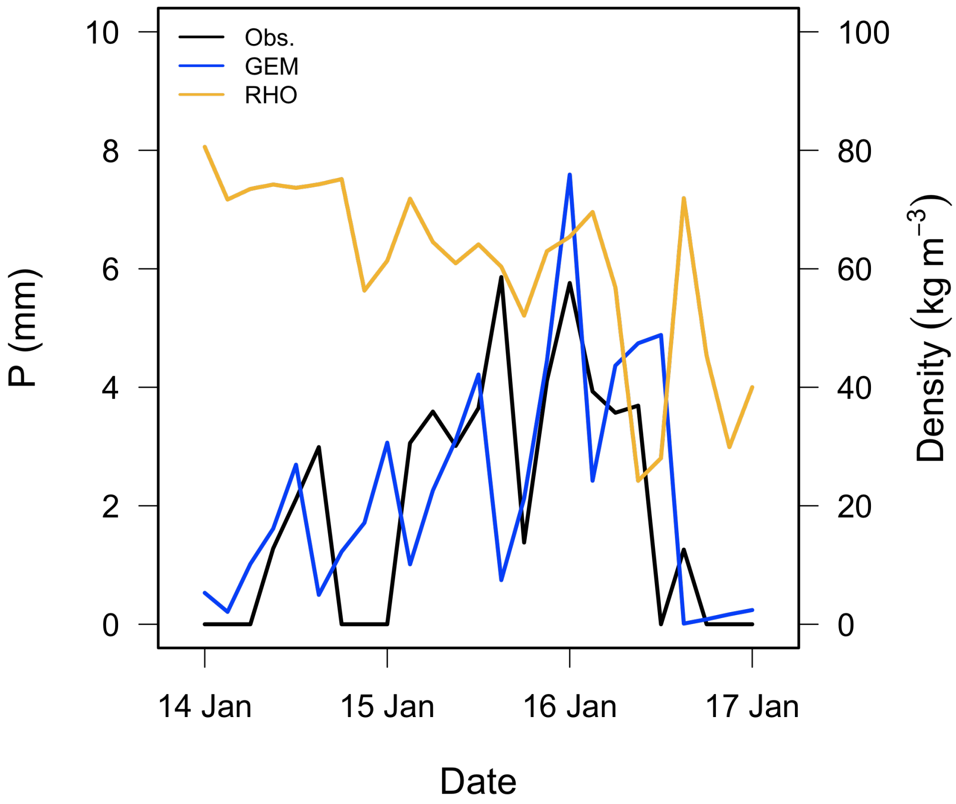


Figure 10: Observed (Obs.) and forecasted (GEM) 3-hourly precipitation amounts as well as the modeled initial new snow density (RHO) for the period of 14 to 16 January 2010 at Mt. Fidelity Study Plot. Values located at the tick marks correspond to the midnight values.