NOWCAST WITH A FORECAST – SNOW COVER SIMULATIONS ON SLOPES

Sascha Bellaire¹*, Bruce Jamieson¹²

¹Dept. of Civil Engineering, University of Calgary, AB, Canada
²Dept. of Geoscience, University of Calgary, AB, Canada

ABSTRACT: The snow cover model SNOWPACK simulates the snow cover formation and evolution based on meteorological parameters. In the past, these parameters were measured by automatic weather stations. Recently, SNOWPACK was also forced with data from numerical weather prediction models (NWP). In this case study we assess the capability of such a model chain to simulate critical layers, i.e. surface hoar and melt-freeze crusts for a virtual north and south-facing slope as well as a level study plot. Meteorological key parameters for the snow cover formation and evolution, e.g. precipitation, radiation, air temperature and relative humidity were measured and compared to the forecasted data to evaluate the performance of the NWP model. Systematic errors of the NWP model were corrected and SNOWPACK finally forced with the adjusted data. Monthly manual profiles observed between January and March – north, south, flat – during the winter of 2010-2011, were compared to the corresponding snow cover simulations. The simulated stratigraphy was found to be in good agreement with the observations. Presence and absence of critical layers – surface hoar and melt-freeze crusts – were modeled with an accuracy of 81%. The simulated snow height tended to be over-estimated for all aspects and the leveled site, especially in March on the south-facing aspect. Nevertheless, the model chain showed a good performance considering the source of the input data. This study showed that such a model chain could become a useful tool for avalanche warning services in the future, especially for data sparse areas.

KEYWORDS: SNOWPACK, snow cover modeling, avalanche warning, numerical weather prediction models, snow cover stratigraphy, model output statistics

1. INTRODUCTION

Changing meteorological conditions force the formation and evolution of the seasonal mountain snow cover. The determining fundamental processes of snow cover formation and evolution are basically understood. Hence, snow cover models were developed to simulate the formation and evolution of the seasonal mountain snow cover based on meteorological input parameters. Advanced snow cover models such as the Swiss model SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002a, 2002b) or the French model CROCUS (Brun et al., 1989, 1992) have been used for various applications during the last years including avalanche forecasting (e.g. Durand et al., 1999; Schirmer et al., 2010). However, all models including snow cover models strongly rely on the quality of the input data, which is often poor considering instrumentation challenges during winter. Furthermore, weather stations with high-quality sensors including radiation sensors, are expensive and therefore the number of available weather stations per avalanche forecasting regions is often limited, especially in North America.

Numerical Weather Prediction models (NWP) are operationally used by weather forecasting services. The horizontal resolution of NWP models has significantly increased during recent years. These high-resolution models are capable of providing all required input parameters for snow cover models, such as air temperature, relative humidity, wind, radiation and precipitation. Gridded data from a NWP model is usually available several times a day making a model chain consisting of a snow cover model and a NWP model almost independent in time and space.

Recently, Bellaire et al. (2011) coupled a snow cover model (SNOWPACK) with a NWP model (GEM15, Environment Canada). Their initial qualitative study showed that the snow cover simulation is in fair agreement with the observations after pre-filtering the forecasted precipitation amounts. However, a quantitative analysis in terms of stratigraphy or critical layer formation was not performed. Iwamoto et al. (2008) also coupled SNOWPACK with a NWP model for an area in Japan. They also found the predicted and measured snow depth in good agreement, but pointed out that the snow
stratigraphy was not consistent with the observations. The first attempt to simulate the snow cover on slopes with the snow cover model SNOWPACK was made by Fierz and Gauer (1998). They simulated the snow cover on a ridge with a north and south-east facing slope. Fierz and Gauer (1998) found no satisfactory agreement between the observed manual profiles and the simulation. The mismatch was partly explained by the fact that the metamorphism module was not fully implemented at this point. The present study aims to assess the capability of SNOWPACK forced by forecasted data from a NWP model (GEM15) to simulate the presence and absence of critical layers – surface hoar and melt-freeze crusts – at a level study site as well as at a north and south-facing slope. Such a model chain could provide additional information for avalanche warning services on the seasonal mountain snow cover, especially in data sparse areas.

2. DATA

The NWP model GEM15 (Mailhot et al., 2005) is operationally in use since 2004 by the Canadian Meteorological Center (CMC). GEM15 (GEM – Global Environmental Multiscale) has a horizontal resolution of 15 km and a vertical resolution of 58 levels. Four times daily at 00 UTC, 06 UTC, 12 UTC and 18 UTC (UTC, Coordinated Universal Time) GEM15 provides forecasted data up to 48-hours with a time step of 3-hours. For this study, forecasted data for seven winters (January – March) between 2005 and 2011 were used. Meteorological parameters were measured during the same six-year period by an automatic weather station (AWS) located at Mt. Fidelity (1905 m a.s.l.), Glacier National Park, British Columbia, Canada (Figure 1). Measured parameter include hourly values of air temperature, relative humidity and precipitation as well as half hour values of wind speed, wind direction, incoming long wave and incoming short wave radiation. During the winter season of 2010-2011 monthly manual profiles - January to March – were recorded on a regular basis at a leveled site, a 10° north-facing and a 30° south-facing slope at Mt. Fidelity at a similar elevation. In total 9 profiles were performed at all three sites. Full depth profiles were only recorded at each site in January (3 profiles). The remaining 6 profiles include at least the layering of the uppermost meter. In these cases the total snow depth was measured.

3. METHODS

For this study the Swiss snow cover model SNOWPACK (release SNOWPACK_20110801) was forced with forecasted data (GEM15) as suggested by Bellaire et al. (2011). The forecasting hours of 3, 6, 9 and 12 after initiation at 00 UTC and 12 UTC were used to create a daily time series with 3-hour time steps. The 12-hour forecasts were assigned to noon and midnight, respectively and were used to force the snow cover model SNOWPACK. Snow cover simulations were carried out for a leveled site as well as a virtual north-facing (30° incline, 0° azimuth) and south-facing slope (30° incline, 180° azimuth). SNOWPACK can be driven using various combinations of input parameters. For this study SNOWPACK was forced using GEM15’s forecasted incoming short and long-wave radiation, the amount of precipitation, air temperature and relative humidity, wind speed and direction. For the winter season of 2010-2011, SNOWPACK was initialized using two manual profiles both recorded on 7 December 2010 for the north and south and a manual profile from 18 December 2010 for the flat field simulation. We used forecasted data from the closest (~ 7 km, W) GEM15 grid-point ($n_x=142; n_y=122$) located at latitude 51.2189° and longitude -117.7938°. Note that the elevation of the grid-point (1815 m a.s.l.)
is lower than the elevation of the study plot (1905 m a.s.l.) where the AWS is located. The performance of the model chain to simulated critical layers (CL) - surface hoar and melt-freeze crusts – was validated using contingency tables (Wilks, 1997) and resulting performance measures (Doswell and Hawkins, 1990). A schematic contingency table is shown in Table 1. For this study we focus on three performance measures the hit rate (HR), which is defined as:

\[
HR = \frac{a}{a + b + c + d}
\]  

(1)

with the poorest hit rate if \(a = d = 0\) and the best performance of the model if \(b = c = 0\). The probability of detection (POD) describes how good the formation of critical layers was modeled and is defined as:

\[
POD = \frac{a}{a + c}
\]  

(2)

A probability of detection of 1 indicates that all critical layers where modeled correctly. Consequently, a probability of non-detection (PON) of 1 indicates that no critical layers was observed nor modeled:

\[
PON = \frac{b}{b + d}
\]  

(3)

Due to connectivity problems with the server of the Canadian Meteorological Center (CMC) during the winter season of 2010-2011 gaps in the used forecasted data occurred. Missing data for this season - air temperature 0.5% (percentage of missing data); relative humidity 12%; incoming short wave radiation 2%, incoming long wave radiation 12%, wind speed 7%, wind direction 7%; precipitation 4% - was supplemented with measured data from the nearby automatic weather station. Note that the periods of missing data do not coincide with the formation of critical layers, i.e. surface hoar and melt-freeze crusts.

4. RESULTS

In this section forecasted meteorological key parameters for snow cover formation and evolution are compared with the observations. Filtering methods are presented where applicable (Section 4.1). A quantitative analysis of presence and absence of critical layers, i.e. surface hoar and melt-freeze crusts, for the winter season 2010-2011 is presented in Section 4.2.

<table>
<thead>
<tr>
<th>Observation</th>
<th>CL</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>No</td>
<td>c</td>
<td>d</td>
</tr>
</tbody>
</table>

### Table 1: Schematic of a contingency table (left) and contingency table of presence and absence of critical layers (CL) for the winter season 2010-2011 (right.)

4.1 Meteorological analysis

To assess the performance of GEM15 to predict meteorological key parameters of snow cover evolution and formation - especially critical layer formation - GEM15 forecasted meteorological data were compared to measured values for six winters between 2005 and 2011. These key parameters are, air temperature, relative humidity, incoming short wave radiation as well as precipitation amounts measured between January and March (Figure 2).

The comparison between forecasted and measured air temperature by month is shown in Figure 2a. The median difference between the measurement and the forecasted air temperature was -1.7 K in January, -1.6 K in February and -0.8 K in March, i.e. a negative or cold bias. The root-mean-square error was 3.6 K for January and February and 2.9 K for March.

The forecasted relative humidity tends to be underestimated by GEM15 for each month. The median differences over six winters were 8.1% in January, 7.5% in February and 2.9 % in March with an overall difference of 7.2% (Figure 2b). Increasing the forecasted relative humidity by 7.2% for each time step and limiting the forecasted relative humidity to 100% results into decreasing root-mean-square errors for each month (January from 11.9% to 10.2%, February from 12.8% to 11.4%, March from 14.1% to 13.8%).

The incoming short wave radiation is one of the most important factors for melt-freeze crust formation. A comparison of forecasted and observed short wave radiation is shown in Figure 2c. For comparison with the forecasted value the maximum incoming short wave radiation measured within the corresponding 3-hour GEM15 time step was chosen. Only values larger than 50 W m\(^{-2}\) were used. The maximum incoming short wave radiation seems to be systematically underestimated by GEM15 for all winter months. Therefore, a filter was developed, which increases the maximum forecasted incoming short wave radiation without significantly changing the general distribution or median values. The filter was...
derived by comparing the forecasted values (min., max. and median) of each month (Figure 2) with the corresponding difference between the forecast and the measurement. The best fit was obtained by a 2nd-order polynomial defined as:

\[
a = 7.86 \times 10^{-4} \cdot b^2 - 1.85 \times 10^{-2} \cdot b - 0.37
\]

with \(a\) the amount of incoming short wave radiation in W m\(^{-2}\) to be added to the forecasted incoming short wave radiation and \(b\) the forecasted incoming short wave radiation of the corresponding time-step. The root-mean-square errors do not significantly change after applying the filter. However, the maximum deviation decreased significantly as shown in Figure 2b.

A comparison of the observed and forecasted precipitation amounts is shown in Figure 2d. Shown are only precipitation amounts larger than 1 mm, which corresponds to the accuracy of the precipitation gauge. GEM15 tends to overestimate the precipitation amounts. The root-mean-square errors were 2.6 mm for January, 3.6 mm for February and 4.5 mm for March. The maximum deviation between the observation and the forecast was 24.8 mm (March). The median difference between observed and forecasted precipitation amounts was 1.52 mm. Dividing each forecasted precipitation amount by this constant factor (Figure 2b) results in an improvement of the root-mean-square error (January 1.8 mm, February 1.9 mm, March 2.7 mm). However, the maximum deviation between observation and forecast is still 15.4 mm. Therefore, a filter was developed using the same method as described above for the incoming short wave radiation. The best fit (\(R^2 = 0.92\)) was obtained by a linear model defined as:

\[
a = 1.02 - 0.66 \cdot b
\]

with \(a\) the amount of precipitation subtracted from forecasted precipitation amounts \(b\). Only precipitation amounts larger than 2 mm were filtered to avoid an increase of small (< 2 mm) precipitation amounts. By applying this filtering method the root-mean-square error decreases to 1.5 for January and February and to 1.8 for March. Forecasted incoming long wave radiation as well as wind speed and direction were found to be in good agreement with the measurements.

Figure 2: Comparison of observed (Obs., clear boxes) and forecasted (GEM, light grey boxes) meteorological parameter a) air temperature (dashed line indicates 0 °C), b) relative humidity, c) incoming short wave radiation and d) precipitation. In addition filtered data are shown in each plot where applicable (dark grey boxes). Boxes span the interquartile range. Whiskers correspond to 1.5 times the interquartile range. Open circles indicate outliers.
4.2 Snow cover analysis

During the 2010-2011 winter season monthly (January, February, March) manual snow profiles were performed on a regular basis at a north and south site and a leveled study plot (Flat) around tree line. During this three month a total number of 11 buried critical layers (2 surface hoar layers and 9 melt-freeze crusts) were found in the 9 manual profiles on the three sites. In four profiles neither a surface hoar layer nor a melt-freeze crust was found.

The contingency table for this winter season is shown in Table 1 (right). The probability of detection was calculated as 91%. All layers but one surface hoar (Flat site in February) were modeled. The probability of non-detection was found to 75%. Three additional crusts and one surface hoar were modeled on the south aspect and flat site, which were not observed (b = 4). POD and PON combined results in a strong overall hit rate of 81%.

Three simulated and the corresponding observed profiles are shown in Figure 3. Shown are profiles from 25 January 2011 (Flat), 28 February 2011 (North) and 22 March 2011 (South). The stratigraphy, i.e. primary grain types according to Fierz et al. (2009) are in general agreement with the observations. The snow depth tends to be over-estimated for both aspects (North and South) as well as for the leveled site and is largest for the south site (compare Figure 2c). All ratios of measured to simulated snow depth for the north, south and flat site are shown in Table 2.

Table 2: Ratio of measured to simulated snow depth for monthly profiles performed at the North, South and Flat site.

<table>
<thead>
<tr>
<th>Month</th>
<th>North</th>
<th>South</th>
<th>Flat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>1.27</td>
<td>0.89</td>
<td>1.13</td>
</tr>
<tr>
<td>Feb</td>
<td>0.87</td>
<td>0.93</td>
<td>0.97</td>
</tr>
<tr>
<td>Mar</td>
<td>0.97</td>
<td>0.64</td>
<td>0.75</td>
</tr>
</tbody>
</table>

5. DISCUSSION

Numerical weather forecasting models became more operational in the last decades. Although the horizontal resolution of these models decreased significantly during the last years the underlying model physics are still not sufficient for complex alpine terrain making a mountain weather forecast challenging. The comparison of forecasted and measured meteorological parameters showed that filtering methods for relative humidity, precipitation as well as incoming short wave radiation became necessary.

Precipitation is one of the most difficult parameter to forecast especially in complex alpine terrain. Therefore, a filtering method for forecasted precipitation amounts is inevitable if new snow amounts, snow depth or rain crusts, need to be modeled with a reasonable accuracy. The presented filtering method reduces the amount of precipitation; however precipitation amounts especially in March are still over-estimated resulting in a general over-estimation of the simulated new snow amounts and consequently snow depth (Table 2).

The elevation of the GEM15 grid point is about 100 m lower compared to the weather station. An elevation correction of the forecasted air temperature based on a dry or wet adiabatic lapse rate would result in an even stronger deviation from the observation. Furthermore, a correction of the general cold bias of GEM15 (Mailhot et al., 2005, ~1.5 K) would nearly equalize the elevation correction depending on the atmospheric conditions. Therefore, no filter was applied to the forecasted air temperature.

GEM15 seemed to under-estimate the peak incoming short wave radiation. This might be related to the 3-hour time step of the model – accumulated incoming short wave radiation, i.e. an average over 3 hours – or an over-estimation of cloud cover and therefore a reduction of incoming short wave radiation. The suggested method increased the maximum peak short wave radiation.

The forecasted relative humidity is under-estimated by GEM15. Without increasing the relative humidity by 7.2% almost no surface hoar would have been modeled. However, the absence of simulated surface hoar might also be related to an under-estimation of mass-flux towards the surface related to an under-estimation of calculated turbulent fluxes as already documented by Stoessel et al. (2010).

Critical layers form under specific atmospheric conditions. Surface hoar will form during moist, calm, clear nights and melt-freeze crusts can form during rain events, warm air advection or periods of high solar radiation. In complex terrain these critical layers can also be spatial variable, e.g. by aspect or elevation band, making the prediction of these layers ambiguous and challenging. All critical layers except for one were modeled by the model chain resulting in a high probability of detection (91%). Only one surface hoar layer was formed, but not buried. SNOWPACK is using a grain size threshold of larger 2 mm to decide...
whether a surface hoar gets buried or not. It seems that SNOWPACK under-estimates the surface hoar size. This is most likely due to the fact that the relative humidity and mass fluxes are under-estimated as outlined above. Three additional crusts and one surface hoar (not observed) were simulated on the flat and south aspect resulting in a lower probability of non-detection (75%). However, the high hit rate of 81% indicates a good overall performance.

The overall stratigraphy seems to be well represented by the model chain in terms of grain types (Fierz et al., 2009). However, the total snow depth tends to be over-estimated especially for the south aspect. Reasons for this over-estimation are the general over-estimation of precipitation, even with an applied filter as well as a likely under-estimation of settlement. So far not much work has been done on snow cover simulations on slopes and potential future improvements can be expected.

Nevertheless, the model chain consisting out of the snow cover model SNOWPACK and the numerical weather prediction model GEM15 provides promising results considering the two complex systems - the atmosphere and the seasonal mountain snow cover - as well as their interaction.

6. CONCLUSIONS

We analyzed six years of weather data as well as monthly manual snow profiles recorded during the winter season of 2010-2011 to assess the performance of a model chain consisting of a snow cover model and a numerical weather prediction model to predict the presence and absence of critical layers.

The presence and absence of critical layers was assessed by comparing monthly observed profiles during the winter season of 2010-2011 to the corresponding simulations. All critical layers, but one surface hoar were modeled and buried leading to a high probability of detection (91%). In addition to the 11 observed critical layers, three melt-freeze crusts and one surface hoar were modeled resulting in a lower probability of non-detection of 75%. However, the hit rate of 81% indicates a good overall model performance. The snow depth tends to be over-estimated at all three sites especially at the south aspect in March.

In conclusion the model chain showed promising potential as a forecasting tool for avalanche warning services, especially in areas where snow cover information are sparse.

ACKNOWLEDGEMENTS

We gratefully acknowledge support by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Helicat Canada Association, the Canadian Avalanche Association,
Mike Wiegele Helicopter Skiing, Teck Mining Company, the Canada West Ski Area Association, the Association of Canadian Mountain Guides, Parks Canada, the Backcountry Lodges of British Columbia Association, the Canadian Ski Guide Association, Backcountry Access and the Canadian Meteorological Center (CMC). For discussions on snow cover modeling we would like to thank Charles Fierz.

REFERENCES


