ASSESSING CRITICAL WET-SNOW AVALANCHE SITUATIONS WITH SPATIALLY DISTRIBUTED SNOW COVER SIMULATIONS

Andrea Bruckmeier[1,2,*], Erwin Rottler[2], Michael Warscher[2], Ulrich Strasser[2], Christoph Mitterer[3]

[1] *Department of Earth Sciences, Montana State University, Montana, United States of America*
[2] *Department of Geography, University of Innsbruck, Austria*
[3] *Avalanche Warning Service Tyrol, Austria*

ABSTRACT: In recent years, physics-based snow cover models have gained importance in supporting avalanche forecasting to better assess critical avalanche conditions. Latest approaches focused on helping and guiding the forecasters in the decision-making process on the most prominent parts describing avalanche danger: the avalanche danger level, snowpack stability or the prevailing avalanche problem. However, it is still challenging to directly link the prevailing avalanche problem (type) obtained from point simulations in a spatially distributed manner. This becomes even more pronounced for warning regions with large gradients in the meteorological variables and/or sparse weather station density. To overcome this issue, we complement simulations of the snow stratigraphy conducted at the point-scale with the 1-D snow cover model SNOWPACK, using openAMUNDSEN, an intermediate complexity and spatially distributed energy-balance-based snow cover model to assess critical wet-snow avalanche situations. This study focuses on a selected avalanche warning region located in the South-Eastern part of Tyrol in Austria (East Tyrol). First, we compare the temporal dynamics of simulated wet snow throughout a winter season using SNOWPACK and openAMUNDSEN at a weather station. Both are tested for a potential relation to days for which the Avalanche Warning Service Tyrol has issued the wet-snow avalanche problem. Next, exemplary examinations of the spatial distribution of the simulated LWC_{index} for days with rain-on-snow and snow melt as the underlying process leading to the wet-snow avalanche problem forecasted by the Avalanche Warning Service Tyrol indicate that openAMUNDSEN has the capability to capture the spatial variability of liquid water in snow depending on elevation and aspect. Satellite-based wet-snow maps from Sentinel-1 images proved to be valuable sources of information on the wet-snow extent in complex mountain terrain and can be used to evaluate model results. Our results indicate that the modelled spatial-temporal information on the liquid water in snow has the potential to support the detection and characterization of periods and areas being subject to the wet-snow avalanche problem. This study provides encouraging new insights that can be used in the further development of operational model applications to support the avalanche problem detection and forecasting.

Keywords: wet snow, openAMUNDSEN, SNOWPACK, liquid water content, avalanche problems, snow cover simulations

1. INTRODUCTION

Wet-snow avalanche activity is still challenging to predict (Madore et al., 2022b). The complex spatial variations and fast-changing dynamics make it difficult to fully understand the interaction between snow mechanics and water within the snowpack (Techel and Pielmeier, 2011; Mitterer et al., 2013). In general, critical wet-snow avalanche conditions are caused by the infiltration of liquid water into the snowpack either through rain or snow melt (McClung and Schaerer, 2006). The process of water percolating through snow leading to instabilities, their precise timing of the onset of a wet-snow avalanche activity and the end of it are key aspects that are still under investigation (Mitterer et al., 2011).

Understanding the process leading to instability of the snowpack in wet-snow conditions is a fundamental prerequisite for subsequent research. According to Denoth (1980) the transition from the so-called pendular regime with dominant capillary forces to the so-called funicular regime with a dominant water flow due to gravity within the snowpack is crucial for wet-snow instabilities. At this stage, when the snowpack contains approximately 7 % liquid water within its pore volume, it becomes unstable, increasing the likelihood of a wet-snow avalanche. As the liquid water percolates through the snowpack some of it (3 %) will remain in the pores of the snow representing the irreducible water content (Colbeck, 1974; Coléou and Lesaffre, 1998; Mitterer et al., 2013). The volumetric liquid water content ($\theta_{w,v}$) can detect variations in wetness of the snow cover, provides indications for instabilities, and thereby serves as an appropriate indicator for wet-snow avalanche activity. It has been tested and applied in various studies (Mitterer et al., 2011; Mitterer and Schweizer, 2013; Koch et al., 2014; Wever

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[*] Corresponding author address:
Andrea Bruckmeier
Montana State University, Department of Earth Sciences
Bozeman, MT 59717-3480, United States of America;
email: andrea.bruckmeier@web.de

et al., 2016; Bellaire et al., 2017; Madore et al., 2022a).

Before Mitterer et al. (2013) introduced the $\text{LWC}_{\text{index}}$ as a reliable predictor for the onset of wet-snow avalanche cycles using $\theta_{w,v}$, the snow depth and the irreducible water content, other approaches have been applied trying to detect the wet-snow avalanche activity. Since $\theta_{w,v}$ is difficult to measure in the field, air temperature was often used as a primary indicator for wet-snow occurrences (Kattelmann, 1984; McClung and Schaerer, 2006). Applying statistical models that included surface and snow temperature proved to be more accurate than focusing only on air temperature (Baggi and Schweizer, 2009; Peitzsch et al., 2012; Mitterer and Schweizer, 2013; Horton et al., 2020). More recently, physically based snow cover models that simulate $\theta_{w,v}$ by calculating or parameterizing the energy balance showed promising results for applying the simulation in an operational context of avalanche forecasting (Bellaire et al., 2017; Morin et al., 2020; Miller et al., 2023; Strasser et al., 2024). The snow cover model SNOWPACK includes precise information on snow stratigraphy at the point scale and is currently used operationally in locations throughout the world (Mitterer and Schweizer, 2014; Bellaire et al., 2017; Miller et al., 2023). However, the interpretation of point simulations over a larger domain (e.g. an avalanche warning region) remains challenging due to complex alpine terrain with strong variations in elevation, slope and aspect over short distances.

In this study, we aim to evaluate the potential of spatially distributed snow simulations using the intermediate complexity snow cover model openAMUNDSEN (Strasser et al., 2024) to support the assessment of critical wet-snow avalanche conditions. Our study site is the micro-region Schober Mountains in East Tyrol, Austria, which in turn lies within the forecasting domain of the Avalanche Warning Service Tyrol. As a first step, we compare the $\text{LWC}_{\text{index}}$ from SNOWPACK point simulation to results from openAMUNDSEN at the weather station *Eselrücken*. We examine if the simulated $\text{LWC}_{\text{index}}$ increases coincide with days the Avalanche Warning Service Tyrol forecasted wet-snow avalanche conditions. Secondly, the ability of openAMUNDSEN to capture spatial variability of wet snow in complex mountain terrain provides potential for identifying areas of wet-snow avalanche activity. Thus, we compare simulation results with satellite-based wet-snow maps (WSMs) from Sentinel-1 data to confirm the extent of the wet-snow avalanche area. The results of both analyses highlight the potential use of openAMUNDSEN to help forecast wet-snow avalanche problems while enhancing the scope of different snow cover models in operational avalanche forecasting.

2. DATA AND METHODS

2.1 Study site

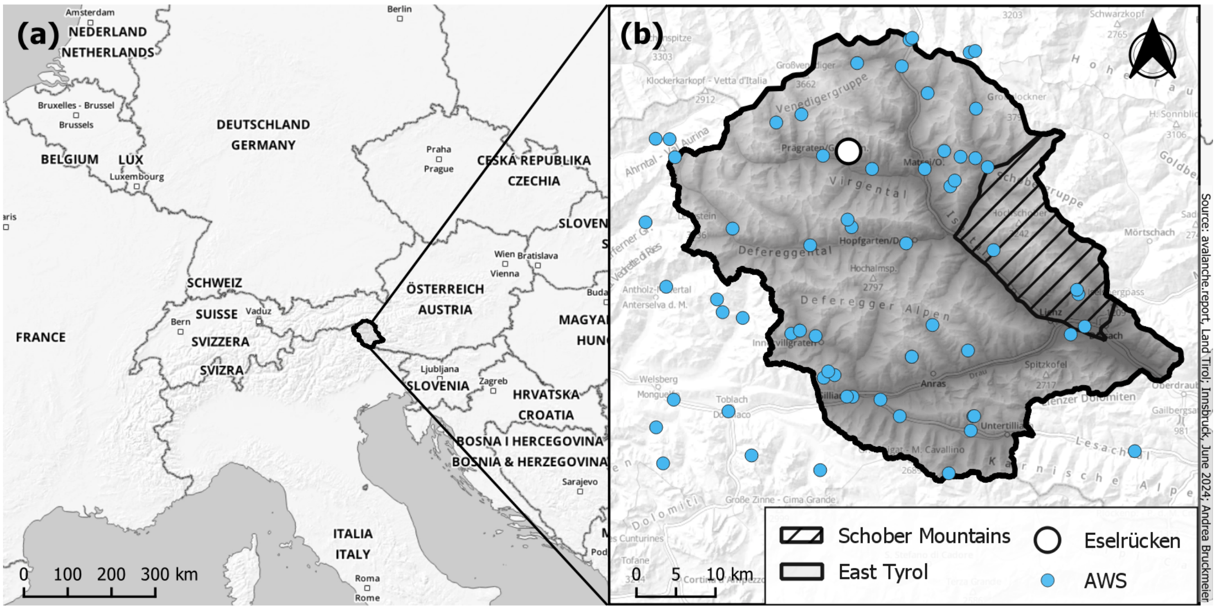
In this study, we focus on the micro-region Schober Mountains in East Tyrol, located south of the Main Alpine Ridge in Austria (Fig. 1a). Several major wet-snow avalanche cycles occurred throughout this region in recent years. For our spatially distributed simulations, we specifically examine the winter seasons of 2019-2020 and 2020-2021. The lowest elevation point within the micro-region is at 648 m.a.s.l. while the highest point is the summit Hochschober with 3242 m.a.s.l.. The study site comprises an area of approximately 247 km^2. Further simulations were conducted and compared with days identified by the Avalanche Warning Service Tyrol as having a wet-snow avalanche problem at the nearby weather station *Eselrücken* for the winter season 2019-2020 (Fig. 1b).

2.2 openAMUNDSEN

We used the distributed snow cover model openAMUNDSEN in 50 m spatial and hourly temporal resolution. The snow cover is simulated using an energy balance approach combined with a snow depth dependent layering scheme distinguishing up to three snow layers (Essery, 2015; Strasser et al., 2024). To force the model, we used meteorological recordings from automated weather stations (AWS) operated by the Avalanche Warning Service Tyrol and Styria, Tiroler Wasserkraft AG (TIWAG), GeoSphere Austria, and the Hydrographic Service of Tyrol (see Fig. 1b). The simulation results for the AWS *Eselrücken* were extracted from an openAMUNDSEN model run for the entire region of East Tyrol. For the micro-region analysis, we focused on a model set-up covering the Schober Mountains using only AWS within or proximate to the area. This reduction was primarily motivated by the need to enhance simulation efficiency and reduce computation time. Within openAMUNDSEN, station-based recordings are spatially interpolated using a combined lapse rate/inverse distance weighting scheme. In our set-up, we define the maximum liquid water content of snow as a fraction of the pore volume, in our case 7% (Coléou and Lesaffre, 1998). When this threshold is exceeded, water drains to the underlying snow layer or out of the snowpack. In order to calculate the volumetric liquid water content of the simulated snow cover ($\theta_{w,v}$), we sum up the amount of liquid water stored in the three snow layers and divide it by the total snow depth. This provides the input for calculating the $\text{LWC}_{\text{index}}$ (Mitterer et al., 2013).

2.3 SNOWPACK

In order to compare the simulated $\theta_{w,v}$ of openAMUNDSEN with results from another snow cover



Source: avalanche.report, Land Tirol; Innsbruck, June 2024; Andrea Bruckmeier

Figure 1: Map (a) shows the overview of a section of Europe with East Tyrol. Map (b) provides a close-up showing the weather station *Eselrücken* (white dot), the test micro-region *Schober Mountains* and the AWSs of which the meteorological recordings were used to run openAMUNDSEN (light blue dots).

model, we used the 1-D snow cover model SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002a,b). SNOWPACK considers the snow stratigraphy for a selected point (usually the location of a AWS) (Bartelt and Lehning, 2002). In this study, SNOWPACK is driven with the meteorological data of the AWS *Eselrücken* (see Fig. 1a). We used this station since it provides all necessary input data for SNOWPACK and because of its southerly exposed location. For the comparison with openAMUNDSEN, we use the simulations on a virtual 38° steep south-facing slope. This corresponds to the characteristics of the openAMUNDSEN grid cell representing the location of the AWS *Eselruecken*.

2.4 LWC$_{\text{index}}$ for model comparison

As a measure for our approaches, we use the LWC$_{\text{index}}$ based on model simulations from SNOWPACK and openAMUNDSEN. The LWC$_{\text{index}}$ is an indicator for wet-snow avalanche activity (Mitterer and Schweizer, 2013; Mitterer et al., 2013) and is defined according to Mitterer et al. (2013):

$$LWC_{\text{index}} = \frac{\theta_{w,v}}{0.03} \tag{1}$$

$\theta_{w,v}$ is the modelled average volumetric liquid water content across all layers of the snowpack. Mitterer et al. (2013) pointed out that the LWC$_{\text{index}}$ is more useful than the $\theta_{w,v}$ itself in terms of determining the development of stability within the snowpack. To interpret the LWC$_{\text{index}}$ four steps need to be considered (Mitterer et al., 2013, 2016): (i) the decrease of stability when the LWC$_{\text{index}}$ increases towards 1 (ii) the timing of maximum instability when the LWC$_{\text{index}}$ is greater than 1 (iii) the return to stability as the LWC$_{\text{index}}$ is lower than 1 again and (iv) the first instability and onset of first wet-snow cycle when the LWC$_{\text{index}}$ for the first time is greater than 0.33.

2.5 Satellite-based wet-snow maps

Furthermore, we compare our spatially distributed model result to satellite-based wet snow maps (WSMs) based on Sentinel-1 images from the AlpSnow project (`https://alpsnow.enveo.at/`), a science activity within the Alpine Regional Initiative from the European Space Agency (ESA). Since the C-band Synthetic Aperture Radar (SAR) signal is highly sensitive towards liquid water in the snowpack, it allows for the detection of areas characterised by wet snow (Nagler et al., 2016; Marin et al., 2020). The WSMs have an original grid spacing of 84.65 m and were resampled to match the openAMUNDSEN simulation grid by using the nearest neighbour method.

2.6 Euregio Avalanche Report

Within our test micro-region, the Avalanche Warning Service Tyrol informs the general public with the so-called Euregio Avalanche Report on the prevailing avalanche conditions. The avalanche.report (`https://avalanche.report/bulletin/latest`) represents a forecast and is published on a daily basis throughout a winter season (December until May). It contains the prevailing avalanche danger, avalanche problem, avalanche pattern and snowpack conditions for the entire region of Tyrol, Austria. For our study, we used days with forecasted wet-snow avalanche problems by the Avalanche Warning Service Tyrol and compared these days to the outputs of SNOWPACK and openAMUNDSEN.

3. RESULTS AND DISCUSSION

3.1 LWC$_{index}$ in SNOWPACK and openAMUNDSEN

Here, we compared the LWC$_{\text{index}}$ simulated with SNOWPACK and openAMUNDSEN at the AWS *Eselrücken* (Fig. 2b). Further, we contrasted forecasted avalanche problems by the Avalanche Warning Service Tyrol with the model outputs.

Our results show that the temporal evolution of the LWC$_{\text{index}}$ of both model outputs displayed a corresponding trend especially for the second half of the winter season. The high values in openAMUNDSEN in December were due to a lower snow height at the beginning of the winter combined with a rain-on-snow event as the LWC$_{\text{index}}$ is very sensitive to snow height (Mitterer et al., 2013). In December, the LWC$_{\text{index}}$ reached the threshold of 0.33 for both model approaches indicating the first wet-snow avalanche cycle.

At the beginning of February, openAMUNDSEN depicted an increase towards 0.75 while the values based on SNOWPACK simulations stayed below 0.2. The increase aligned well with a predicted wet-snow avalanche problem (shaded areas in Fig. 2a). When compared with SNOWPACK during this period, openAMUNDSEN better predicted days with avalanche activity through an increase of the LWC$_{\text{index}}$.

At the end of February, the Avalanche Warning Service Tyrol forecasted a wet-snow avalanche problem in the region. Both models showed a clear rise in the LWC$_{\text{index}}$, indicating increased avalanche activity. The openAMUNDSEN model predicted values up to 1.25, while the SNOWPACK model showed values around 0.7. Both models captured this event. According to the Avalanche Warning Service Tyrol, areas at lower elevations and sun-exposed slopes were particularly affected.

On March 5, the Avalanche Warning Service Tyrol forecasted a wet-snow avalanche problem driven by rainfall. Neither model indicated wet-snow avalanche activity on this day. In this case, the LWC$_{\text{index}}$ seemed to be less reliable detecting wet-snow occurrences due to rain compared with scenarios where snow melt is the cause of liquid water in the snowpack (Mitterer et al., 2013, 2016). More likely, however, is uncertainty associated with the avalanche.report being a subjective human forecast needs to be considered. On March 29, 2020 this uncertainty of knowledge might be the reason for the scenario that the simulation outputs showed a strong increase in the LWC$_{\text{index}}$, while no wet-snow avalanche problem was issued be the Avalanche Warning Service Tyrol. This sharp rise in LWC$_{\text{index}}$ does not explain the low danger level on those days for the entire region.

Towards the middle of March, spring-like conditions started to prevail, i.e. diurnal cycles of freezing during night and radiation induced melting during the day. The LWC$_{\text{index}}$ can reasonably detect such scenarios according to Mitterer et al. (2016). This aligns with our findings for the wet-snow cycles in the middle of March and during April for both models. Looking at the values of the models' outputs the simulated LWC$_{\text{index}}$ from openAMUNDSEN oscillates around 1.5, while results from SNOWPACK oscillate around 1. A reason for this discrepancy might be the parametrization of the maximum $\theta_{w,v}$ of the pore volume or the different layering approaches applied by the two models.

The openAMUNDSEN LWC$_{\text{index}}$ shows a sharp drop in the second half of April. This is due to the disappearance of the seasonal snow cover in the model simulation. The short peak on April 30 is another precipitation event depicted in both models with a sharp rise and fall of the LWC$_{\text{index}}$. Again, this shows the sensitivity of the LWC$_{\text{index}}$ to snow depth.

Both modelling approaches generally captured the main seasonal dynamics of the LWC$_{\text{index}}$ in the region and detected spring-like scenarios and associated wet-snow avalanche danger due to melt. Uncertainty in case of the prediction of wet-snow avalanche problems by the Avalanche Warning Service Tyrol has to be considered interpreting the results. Overall, openAMUNDSEN shows higher values when it comes to melt-freeze cycles (Fig. 2a and b). The difference between models never exceeded 1 except for periods in December and April where openAMUNDSEN does not display any snow height (Fig. 2b).

3.2 Spatially distributed wet-snow comparison

The comparison of the spatial distribution of the LWC$_{\text{index}}$ simulated with openAMUNDSEN with the WSM suggests that openAMUNDSEN can capture the spatial variability of wet snow in complex mountain terrain (Fig. 3). According to the Avalanche Warning Service Tyrol, the main reason for the wet-snow avalanche problem on April 20 was rain between 1800 m.a.s.l. and 2800 m.a.s.l. (Fig. 3a and b). On that day, openAMUNDSEN results indicate decreasing values of LWC$_{\text{index}}$ in elevations above 2800 m.a.s.l. and high LWC$_{\text{index}}$ values on all aspects below approx. 2800 m.a.s.l.. Lower elevations are snow-free. The determination of the snow line in openAMUNDSEN seems to have worked well for this event. The wet-snow extent detected by Sentinel-1 generally coincides with openAMUNDSEN simulations. However, the model output captures the liquid water as $\theta_{w,v}$ for the entire snowpack depth, whereas Sentinel-1 products only indicate if

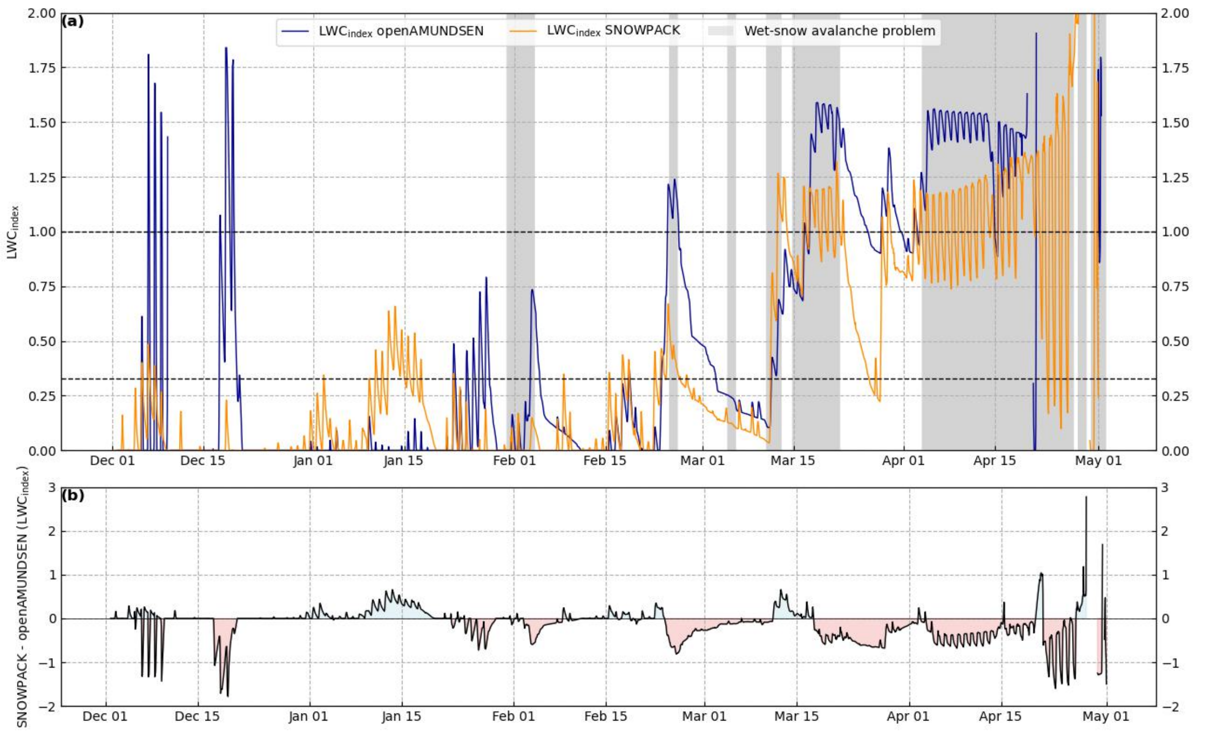


Figure 2: (a) $\mathrm{LWC}_{\mathrm{index}}$ simulated with SNOWPACK (orange line) and openAMUNDSEN (blue line) at the AWS *Eselrücken* for the winter season 2019-2020. The grey bars show the days on which the Avalanche Warning Service Tyrol assessed a wet-snow avalanche problem. The dotted horizontal black lines indicate the thresholds for the interpretation of the $\mathrm{LWC}_{\mathrm{index}}$.
(b) Differences between the $\mathrm{LWC}_{\mathrm{index}}$ simulated using SNOWPACK and openAMUNDSEN with light-blue (pink) areas indicating periods when the modelled $\mathrm{LWC}_{\mathrm{index}}$ in openAMUNDSEN is lower (higher) than the simulated $\mathrm{LWC}_{\mathrm{index}}$ from SNOWPACK.

the upper part of the snowpack is wet or dry. Further, the comparison is limited as the satellite-based data only offers a binary classification of either wet or dry snow. In addition, the satellite-based data does not provide information in forested areas (Nagler et al., 2016).

Based on the avalanche report issued by the Avalanche Warning Service Tyrol, April 3, 2021 was characterized by a typical springtime situation with a diurnal melt-freeze cycle. The avalanche danger increased during the day especially on southerly exposed slopes. Both model simulations and satellite-based WSMs captured the different conditions prevailing on south- and north-facing slopes (Fig. 3 c and d). High $\mathrm{LWC}_{\mathrm{index}}$ values existed on south-facing slopes, while on north-facing slopes the $\mathrm{LWC}_{\mathrm{index}}$ remained low.

Our results indicated that model simulations as well as satellite-based WSMs can capture differences depending on aspect when the wet-snow avalanche problems were caused by temperature and/or radiation driving snow melt. The usage of an energy balance approach for distributed snow modelling proved to be suitable to capture of complex spatial pattern of wet snow through the $\mathrm{LWC}_{\mathrm{index}}$ in mountain terrain.

The satellite-based WSMs represent an independent source of wet-snow extent and a valuable data source to evaluate modelling results. One drawback of the satellite-based WSMs, however, is that they only provide the wet-snow extent in a binary wet/dry snow classification. No information on the amount of the $\theta_{w,v}$ is provided. The amount of liquid water within the snowpack, however, is important to distinguish if an avalanche is more likely to be a small surficial wet-loose avalanche or if it can be a deep wet-slab avalanche of larger size (McClung and Schaerer, 2006). The integration of satellite-based wet-snow data into the snow cover modelling by means of an ensemble-based assimilation is a potential way forward.

Our results indicate that distributed snow simulations using intermediate complexity snow models such as openAMUNDSEN have the potential to support the identification of critical wet-snow avalanche conditions in spatial and temporal resolutions relevant for avalanche forecasting services.

4. CONCLUSION

In this study, we assessed the potential of the intermediate complexity snow cover model openAMUNDSEN supporting the determination of the wet-snow avalanche activity. We compared openAMUNDSEN model results with the simulations of SNOWPACK as well as with satellite-based WSMs.

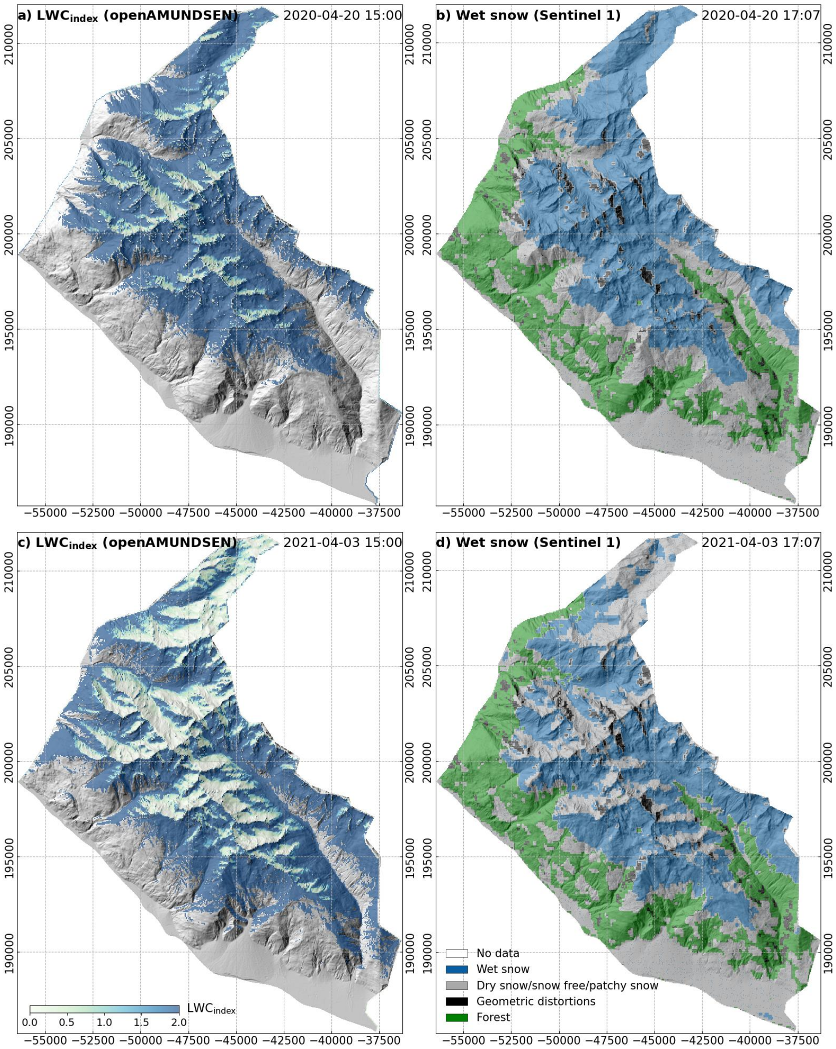


Figure 3: Simulated $\mathrm{LWC}_{\mathrm{index}}$ based on openAMUNDSEN and satellite-based WSMs from Sentinel-1 images for the Schober Mountains, East Tyrol (Austria) for the 20/04/2020 (a and b) and 03/04/2021 (c and d). In the background of the figures, the hillshade is displayed.

The comparison with the $\mathrm{LWC}_{\mathrm{index}}$ simulated with SNOWPACK and openAMUNDSEN indicated that both models can show the temporal variability of wet snow in the snowpack over a winter season. Both models captured the melt-freeze cycles during springtime situations (Fig. 2) and increases in the simulated $\mathrm{LWC}_{\mathrm{index}}$ indicating critical snow instabilities generally coinciding with days the Avalanche Warning Service Tyrol announced wet-snow avalanche problems. However, uncertainty exists in predicting wet-snow avalanche problems, since we do not know if the forecast actually happened. Differences in the magnitude of the simulated $\mathrm{LWC}_{\mathrm{index}}$ might be due to the different snow layering schemes of the models, the definition of the maximum $\theta_{w,v}$ of the pore volume in the model parameterization and variations in the modelled snow height. Further investigation in other regions and for other winter seasons are required in this regard.

Furthermore, our investigation indicates that openAMUNDSEN can capture the variability of $\mathrm{LWC}_{\mathrm{index}}$ in complex mountainous terrain spatially and temporally, which is relevant for the determination of critical wet-snow avalanche conditions. The energy balance approach selected enables the assessment of the variability depending on elevation and aspect. The comparison with satellite-based WSMs from Sentinel-1 images confirms these findings. Future work examining snow line during rain-on-snow events is required for more robust detection of potential wet-snow avalanche conditions with spatially distributed snow modelling.

This study provides valuable new insights into the capability of spatially distributed snow simulations using intermediate complexity snow models such as openAMUNDSEN to support the determination of the wet-snow avalanche problem. Further investigations are required to test an operational work flow combining (i) detailed simulations of the snow stratigraphy for selected points, (ii) spatially distributed snow simulations using intermediate complexity snow models and (iii) satellite-based snow data. It has the potential to provide insights into the state of the snow cover on a synoptic scale supporting the detection and the forecast of critical wet-snow avalanche conditions.

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References

Baggi, S. and Schweizer, J.: Characteristics of wet-snow avalanche activity: 20 years of observations from a high alpine valley (Dischma, Switzerland), Natural Hazards, 50, 97–108, 2009.

Bartelt, P. and Lehning, M.: A physical SNOWPACK model for the Swiss avalanche warning: Part I: numerical model, Cold Regions Science and Technology, 35, 123–145, 2002.

Bellaire, S., van Herwijnen, A., Mitterer, C., and Schweizer, J.: On forecasting wet-snow avalanche activity using simulated snow cover data, Cold Regions Science and Technology, 144, 28–38, 2017.

Colbeck, S. C.: The capillary effects on water percolation in homogeneous snow, Journal of Glaciology, 13, 85–97, 1974.

Coléou, C. and Lesaffre, B.: Irreducible water saturation in snow: experimental results in a cold laboratory, Annals of glaciology, 26, 64–68, 1998.

Denoth, A.: The pendular-funicular liquid transition in snow, Journal of Glaciology, 25, 93–98, 1980.

Essery, R.: A factorial snowpack model (FSM 1.0), Geoscientific Model Development, 8, 3867–3876, 2015.

Horton, S., Towell, M., and Haegeli, P.: Examining the operational use of avalanche problems with decision trees and model-generated weather and snowpack variables, Natural Hazards and Earth System Sciences, 20, 3551–3576, 2020.

Kattelmann, R.: Wet slab instability, in: Proceedings International Snow Science Workshop, Aspen, Colorado, USA, pp. 24–27, 1984.

Koch, F., Prasch, M., Schmid, L., Schweizer, J., and Mauser, W.: Measuring snow liquid water content with low-cost GPS receivers, Sensors, 14, 20 975–20 999, 2014.

Lehning, M., Bartelt, P., Brown, B., and Fierz, C.: A physical SNOWPACK model for the Swiss avalanche warning: Part III: Meteorological forcing, thin layer formation and evaluation, Cold Regions Science and Technology, 35, 169–184, 2002a.

Lehning, M., Bartelt, P., Brown, B., Fierz, C., and Satyawali, P.: A physical SNOWPACK model for the Swiss avalanche warning: Part II. Snow microstructure, Cold regions science and technology, 35, 147–167, 2002b.

Madore, J., Fierz, C., and Langlois, A.: Investigation into percolation and liquid water content in a multi-layered snow model for wet snow instabilities in Glacier National Park, Canada, Frontiers in Earth Science, 10, 898 980, 2022a.

Madore, J., Fierz, C., and Langlois, A.: Investigation into percolation and liquid water content in a multi-layered snow model for wet snow instabilities in Glacier National Park, Canada, Frontiers in Earth Science, 10, 898 980, 2022b.

Marin, C., Bertoldi, G., Premier, V., Callegari, M., Brida, C., Hürkamp, K., Tschiersch, J., Zebisch, M., and Notarnicola, C.: Use of Sentinel-1 radar observations to evaluate snowmelt dynamics in alpine regions, The Cryosphere, 14, 935–956, doi:10.5194/tc-14-935-2020, URL https://tc.copernicus.org/articles/14/935/2020/, 2020.

McClung, D. and Schaerer, P.: The avalanche handbook, 3rd ed., The Mountaineers Books, Seattle, WA, 2006.

Miller, Z., Horton, S., Mitterer, C., and Peitzsch, E.: Comparing snowpack meteorological inputs to support regional wet snow avalanche forecasting, in: International Snow Science Workshop 2023, pp. 264–271, 2023.

Mitterer, C. and Schweizer, J.: Analysis of the snow-atmosphere energy balance during wet-snow instabilities and implications for avalanche prediction, The Cryosphere, 7, 205–216, 2013.

Mitterer, C. and Schweizer, J.: Comparing models of different levels of complexity for the prediction of wet snow avalanches, in: Proceedings ISSW, pp. 9–14, Citeseer, 2014.

Mitterer, C., Hirashima, H., and Schweizer, J.: Wet-snow instabilities: comparison of measured and modelled liquid water content and snow stratigraphy, Annals of Glaciology, 52, 201–208, 2011.

Mitterer, C., Techel, F., Fierz, C., and Schweizer, J.: An operational supporting tool for assessing wet-snow avalanche danger, in: Proceedings ISSW, vol. 33, pp. 334–338, Citeseer, 2013.

Mitterer, C., Heilig, A., Schmid, L., van Herwijnen, A., Eisen, O., and Schweizer, J.: Comparison of measured and modelled snow cover liquid water content to improve local wet-snow avalanche prediction, in: International Snow Science Workshop Proceedings, vol. 5, 2016.

Morin, S., Horton, S., Techel, F., Bavay, M., Coléou, C., Fierz, C., Gobiet, A., Hagenmuller, P., Lafaysse, M., Ližar, M., et al.: Application of physical snowpack models in support of operational avalanche hazard forecasting: A status report on current implementations and prospects for the future, Cold regions science and technology, 170, 102 910, 2020.

Nagler, T., Rott, H., Ripper, E., Bippus, G., and Hetzenecker, M.: Advancements for snowmelt monitoring by means of Sentinel-1 SAR, Remote Sensing, 8, 348, 2016.

Peitzsch, E. H., Hendrikx, J., Fagre, D. B., and Reardon, B.: Examining spring wet slab and glide avalanche occurrence along the Going-to-the-Sun Road corridor, Glacier National Park, Montana, USA, Cold regions science and technology, 78, 73–81, 2012.

Strasser, U., Warscher, M., Rottler, E., and Hanzer, F.: openAMUNDSEN v 0.8. 3: an open source snow-hydrological model for mountain regions, EGUsphere, 2024, 1–25, 2024.

Techel, F. and Pielmeier, C.: Point observations of liquid water content in wet snow–investigating methodical, spatial and temporal aspects, The Cryosphere, 5, 405–418, 2011.

Wever, N., Vera Valero, C., and Fierz, C.: Assessing wet snow avalanche activity using detailed physics based snowpack simulations, Geophysical Research Letters, 43, 5732–5740, 2016.