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Atmosphere-permafrost relationship in the Austrian Alps

G. Heinrich, M. Bavay, C. Fierz, M. Lehning, M. Phillips

Name of the candidate and institution: Dr. Georg Heinrich (WG3), Climate Change of Mountain Regions Research Group (CC-MoRe), Department of Geography and Regional Science, University of Graz, Austria

Name of host institute: WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland (ES1404 member: Dr. Charles Fierz; WG1, WG2, and MC)

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Contents

1. Purpose of the STSM

It can be expected that future climate change in the Alpine region with a projected warming during summer of about 2 °C until 2050 (Gobiet et al., 2014) has a major impact on the ground thermal regime. Related thawing effects and permafrost warming have the potential to trigger mountain hazards such as rock falls and debris flows that are highly relevant for people living in the affected regions. However, the estimation of Alpine permafrost distribution is a challenging task due to high temporal and spatial variability of snow cover, complex topography and soil properties.

In this respect, it is important to better understand the complex atmosphere-snow-permafrost interplay, enhancing the knowledge of processes relevant for permafrost degradation. Therefore, a physical- and process-based model will be applied for the site of Hoher Sonnblick which has the advantage of covering high quality monitoring of the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere (Schöner et al., 2012), an important pre-requisite for driving and evaluating the applied permafrost model. For this purpose we will use the *SNOWPACK* model (Bartelt and Lehning, 2002; Lehning et al. 2002a; Lehning et al. 2002b) which is developed by the Swiss WSL Institute for Snow and Avalanche Research SLF (WSL/SLF) in Davos.

The main aim of the STSM was to get familiar with the models developed at the WSL/SLF in order to set up a shared model framework which will significantly strengthen the cooperation between WSL/SLF and Climate Change of Mountain Regions Research Group (CC-MoRe). The shared model framework includes *MeteoIO* (Bavay and Egger, 2014), a data pre-processing tool developed at WSL/SLF, as well as *SNOWPACK*, a multi-purpose snow and

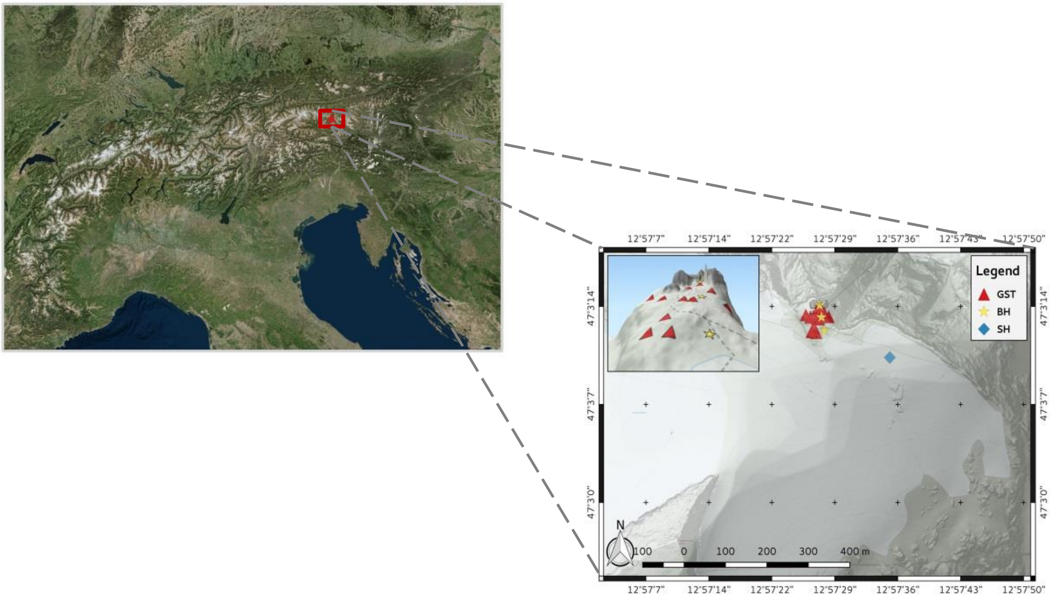

Fig. 1 Study site of Hoher Sonnblick (3106 m a.s.l.) in Salzburg, Austria. GST: Ground surface temperature measurements; BH: Borehole sites (20 m depth); SH: Snow depth measurement. Meteorological measurements are taken at the observatory at the summit of Hoher Sonnblick.

land-surface model, which focuses on a detailed description of the mass and energy exchange between the snow, the atmosphere and optionally with the vegetation cover and the soil and, therefore, fits perfectly for studying the atmosphere-snow-permafrost coupling. Both model frameworks, *MeteoIO* as well as *SNOWPACK*, were successfully applied with the supervision and support of the “Snow cover and Micrometeorology” research group at WSL/SLF. Very first (preliminary) results of the parametrized incoming long-wave radiation as well as simulated snow height at Hoher Sonnblick (3106 m a.s.l.) demonstrate the challenges related to modelling approaches in high-alpine environments. However, the improvement of the modelling results and extensive evaluation of the results was not subject of the STSM and will be investigated in ongoing research in collaboration with WSL/SLF.

2. Description of work and main results obtained

The duration of the STSM was two weeks from 15.08.2016 to 29.08.2016. During that time, I was first introduced to the data pre-processing tool *MeteoIO*. This tool was used in combination with own developed tools to prepare a dataset (mainly data filtering, data generation, and gap filling) spanning a period of 5 years at Hoher Sonnblick. This dataset was then further applied in order to perform a first test simulation with *SNOWPACK*. During the entire STSM, the collaborators promoted several discussions with other colleagues at the host institution to get additional feedback on this research.

2.1 Description of study site and data

The Hoher Sonnblick is located in the Austrian Central Alps (see Fig. 1) and is characterised by the complex geology of the “Tauernfenster”. The summit of Hoher Sonnblick is at an elevation of 3106 m a.s.l. and is part of the Alpine main ridge, which is a clear climate divide between the generally wetter north and the drier south (Auer et al., 2002). Both the northern and southern side of Hoher Sonnblick are covered by small glaciers (ca. 1 km^2) which are subject of detailed glaciological investigations. The Sonnblick observatory at the summit of Hoher Sonnblick is an outstanding research station covering studies and monitoring of the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere (Schöner et al., 2012).

Spatial characteristics as well as temporal changes of the climate of Hoher Sonnblick and its surrounding area were described in many studies (e.g., Auer et al., 2002). Due to the emission of anthropogenic greenhouse gases (GHGs), air temperature has increased by about 2 °C since the beginning of the meteorological observations at Hoher Sonnblick in 1886. Consequently, the mean percentage of solid precipitation on total precipitation during summer has significantly decreased by about 15 % to 20 % (Auer et al., 2002). Additionally, the number of frost days and ice days has clearly decreased. Climate projections for the Alpine region show a continuing temperature increase for state-of-the-art GHG emission scenarios (e.g., Heinrich et al. 2013). However, large uncertainties remain especially for the precipitation projections. Driven by the projected temperature increase, snow cover is also expected to drastically decrease below 1500 m to 2000 m and natural hazards related to glacier and permafrost retreat are expected to become more frequent (Gobiet et al. 2014).

The observational data we use in this study are from the Austrian Central Institute for Meteorology and Geodynamics (ZAMG). The dataset comprises measured atmospheric data on a 10-minute and daily basis, borehole data, as well as snow depth measurements. The atmospheric data which are required at minimum to drive *SNOWPACK* are air temperature, precipitation amount, incoming shortwave radiation, relative humidity, and wind speed. This data is available on a 10-minute basis since 1998 and for further application the data is aggregated to an hourly basis. Due to the long history of the Sonnblick observatory, some of the daily data (e.g. air temperature) extends far back to 1886. Since 2011, high quality radiation data as part of the Austrian radiation network (ARAD; Olefs et al., 2016) is available at Hoher Sonnblick. The ARAD data is part of the Baseline Surface Radiation Network (BSRN), a worldwide radiation network with a very high level of data quality requirements.

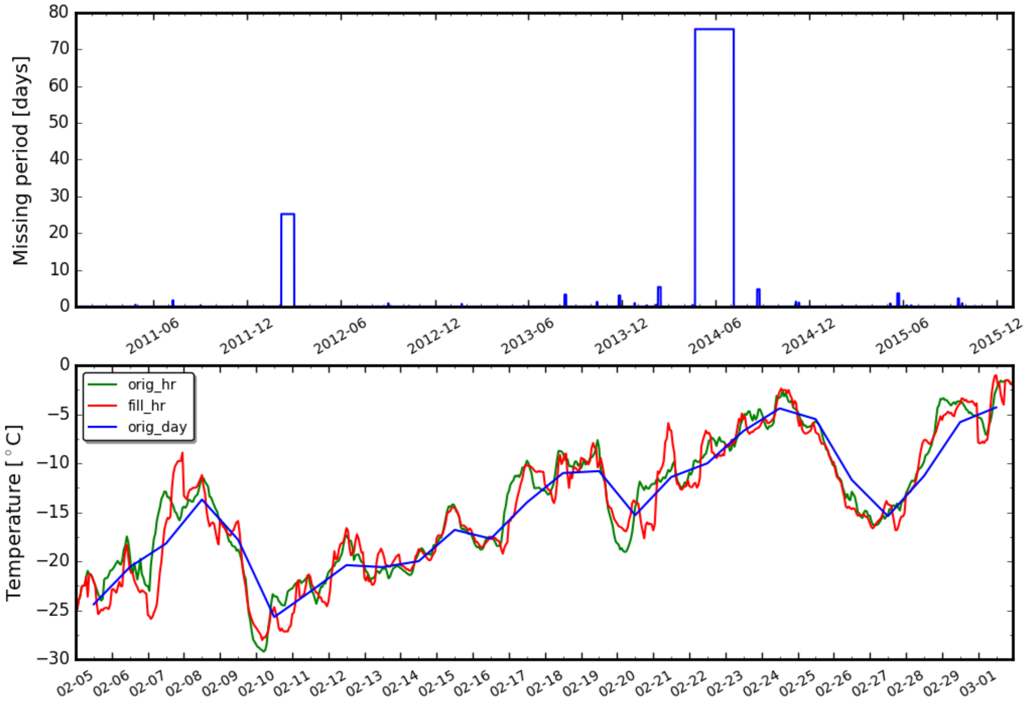

Fig. 2 Top panel: Periods with missing data for precipitation. Bottom panel: Reconstruction of hourly air temperature *(fill_hr)* for the period 2012-02-05 to 2012-03-01 using daily mean air temperature (*orig_day*) from Hoher Sonnblick and the daily cycle from the nearby mountain station Rudolfshuette. The green line shows the original hourly time series (*orig_hr*).

In a first step, we concentrate on the five-year period 2011 to 2015 in order to test the developed tool for filling missing values in the time series as well as several parameterization schemes for incoming longwave radiation (ILWR). Finally, the data of that period is then pre-processed in order to run the *SNOWPACK* model.

2.2 Data pre-processing

Filling of missing data

The atmospheric input data shows several missing data over various period lengths in the time series and filling these gaps with physically consistent and reasonable information is an important prerequisite in order to drive the physically and process-based model *SNOWPACK*. Any inaccuracy on the input parameters will have an impact on the quality of the simulation and SNOWPACK will exclude data points that are not consistent with other parameters (e.g., precipitation occurring simultaneously with dry air will be refused).

In a first step, gaps over short periods up to three hours are linearly interpolated (except for precipitation) which seems to be a reasonable assumption regarding the pronounced daily cycle of certain parameters such as e.g. air temperature or global radiation. However, especially precipitation shows relative large gaps in the order of several days or even up to

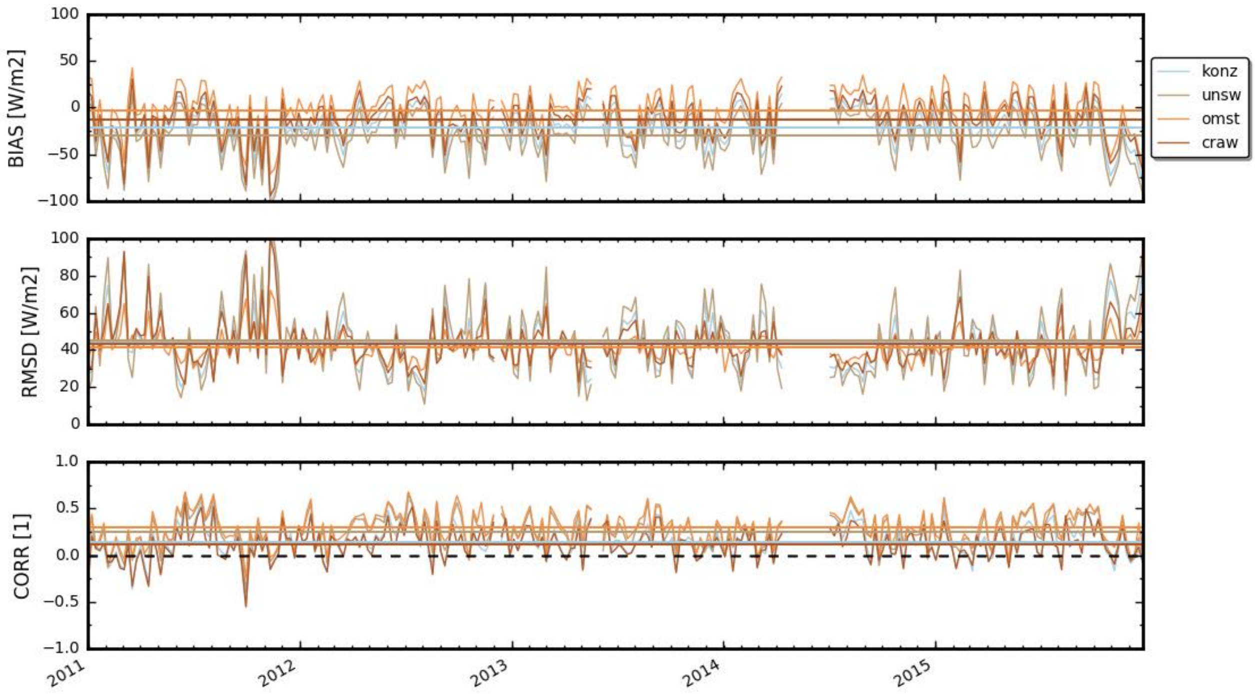

Fig. 3 Performance of the applied empirical all-sky ILWR parameterization schemes at Hoher Sonnblick. The panels depict the running 24 hour bias (upper panel), root mean square deviation (middle panel), and correlation coefficient (lower panel) between modelled and measured ILWR smoothed over a window of 14 days.

weeks (see Fig. 2) and simple interpolation algorithms cannot be applied. In such cases, we use the information of the daily observations which is available in most cases when missing data on the hourly basis occur. In order to generate hourly data from the available daily data, we currently superimpose the daily cycle of all parameters simultaneously from the closest ZAMG mountain station Rudolfshuette (~26 km linear distance, 2317 m a.s.l). Fig. 2 depicts the daily mean as well as the daily cycle of the original and reconstructed hourly air temperature during the period 2012-02-05 to 2012-03-01. As it can be seen, the reconstructed data well represents the day-to-day variation while the deviations on the hourly basis show larger deviations. However, this is just a first implementation of the method and it will be further developed and evaluated in future in order to automatically select the most similar station with respect to the daily cycle of available parameters from a set of well-defined nearby stations.

Parameterization of incoming longwave radiation

Incoming longwave radiation is an important source of energy for snow melt especially during cloudy periods and in high-latitude environments (Sicart et al., 2006; Mölg et al., 2009). Moreover, the parameterization of incoming longwave radiation is an important prerequisite for extending our simulations to periods without ILWR measurements i.e. before the installation of the ARAD measurements in 2011. Furthermore, the ARAD dataset is also

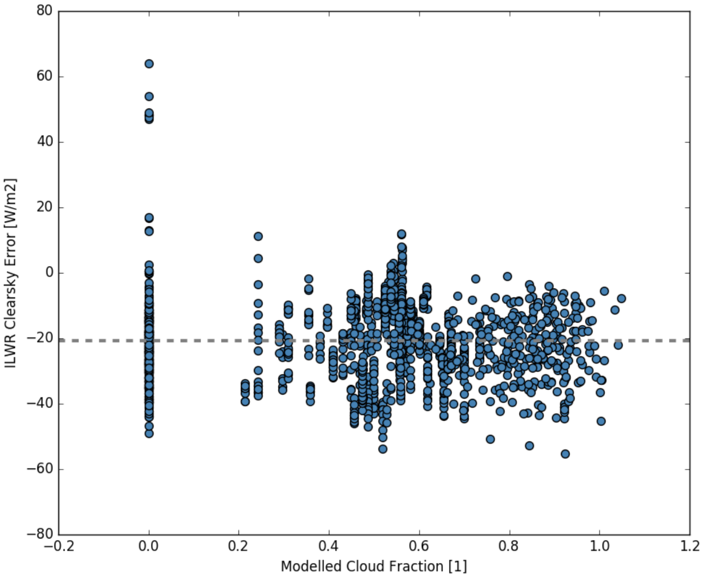

Fig. 4 Error of the Dilley clear-sky parameterization scheme on clear-sky days at Hoher Sonnblick.

affected by periods with missing data and, therefore, the gaps have to be filled with reasonable data. To address these issues, we used the *MeteoIO* library in order to generate ILWR by applying several state-of-the-art and widely applied empirical parameterization schemes (for further information on the applied parameterization schemes we refer to the *MeteoIO* documentation available at https://models.slf.ch/doc-server/meteoio/html/generators.html.) Fig 3. shows the performance of several tested all-sky parameterization schemes: *konz* from Konzelmann et al. (1994), *unsw* from Unsworth and Monteith (1975) coupled with a clear sky emissivity following Dilley and O'brian (1998) (in the following just Dilley), *omst* from Omstedt (1990), and *craw* following Crawford and Duchon (1999). The results show that all parameterizations are subject to a negative bias (overestimation of ILWR) of up to -30.2 W/m^2 for the Unsworth scheme. The lowest bias with -2.9 W/m^2 is obtained for the Omstedt scheme. Fig. 3 also reveals that positive biases are mostly obtained during summer months (e.g. June, July, and August). The root mean square deviation (RMSD) shows values of about 40 W/m^2 for all parameterizations. The correlation coefficient with values below 0.5 is relative low for all schemes.

In order to cross-check the results, we computed the Unsworth parameterization for several other mountain stations in Switzerland with ILWR measurements comprising Davos, Jungfraujoch, Samedan, and Weißfluhjoch. The results reveal high variability in the performance of modelled ILWR among stations (not shown here). We therefore further investigated the potential of enhancing the performance of the ILWR paramterizations by optimizing the empirical derived parameters within the schemes. As a test case we evaluated the Dilley clear-sky parameterization scheme for clear-sky days with no observed cloud cover at Hoher Sonnblick.

Fig. 4 depicts that the error of the modelled clear-sky ILWR with the original parameters (observed minus modelled) is, as expected, independent of the modelled cloud cover while the parameterization shows a negative bias of about 20 W/m^2. However, the effect of wrongly simulated cloud cover on modelled all-sky ILWR is yet to be studied and will be subject of future investigations. The optimisation of the three free parameters in the Dilley scheme was achieved by a latin-hypercube-sampling approach (Iman et al., 1981) with 10 000 random samples, assuming a uniform distribution of the parameter values in the range of ± 20 % of the original values. Optimizing the parameters significantly reduces the RMSD (from 25.7 W/m^2 to 14.2 W/m^2) and the bias (from -21.2 W/m^2 to -0.1 W/m^2), while the correlation coefficient remains at the same level of 0.9.

The results of this small study suggest an optimization of the parameters for the Dilley clear-sky parameterization in order to get rid of the bias. However, further investigations on the stability of the optimized parameters are required which could be achieved by e.g. cross-validation of derived parameters in the time domain. Furthermore, we need to investigate the reason for the low correlation coefficients of the all-sky parameterization schemes which might be related to deficiencies in the calculation of cloud cover.

2.3 SNOWPACK simulation

SNOWPACK is a multi-purpose snow and land-surface model, which focuses on a detailed description of the mass and energy exchange between the snow, the atmosphere and optionally with the vegetation cover and the soil and, therefore, fits perfectly for studying the atmosphere-snow-permafrost coupling. Further information and a detailed description of the model can be found in Bartelt and Lehning (2002), Lehning et al. (2002a), and Lehning et al. (2002b).

In a very first step, we performed a test simulation with *SNOWPACK* using a reasonable configuration of the model (not further discussed here) and the meteorological input data we prepared during the STSM. In this respect, we want to emphasize that *SNOWPACK* offers many configuration options in order to optimize the simulations which could yet not be tested due to lack of time. However, studies on the optimal model set-up including an in-depth analysis of the associated uncertainties are subject to ongoing research and will be performed in collaboration with WSL/SLF. Therefore, the following results of the first test simulation at

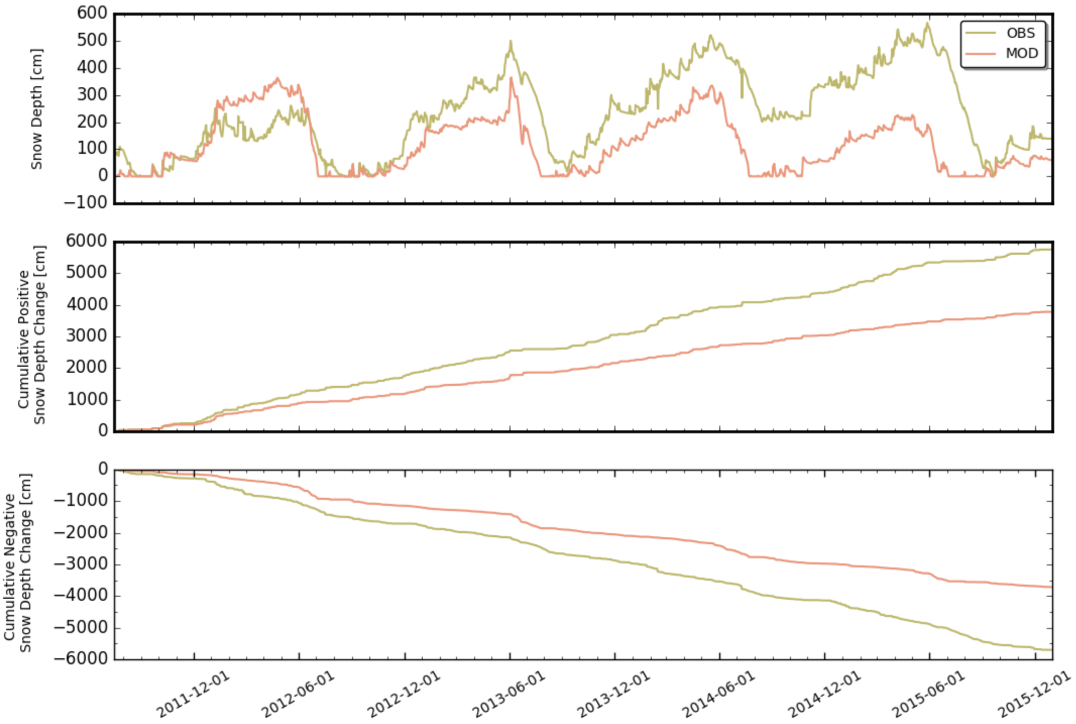

Fig. 5 Top panel: Comparison of observed (OBS) and modelled (MOD) snow depth at Hoher Sonnblick. Middle panel: Comparison between observed and modelled cumulative positive snow depth change. Lower panel: Comparison between observed and modelled cumulative negative snow depth change.

Hoher Sonnblick are only preliminary and there is a lot of potential to improve the skill of the simulation. Fig. 5 shows simulated vs. observed snow depth as well as the cumulative positive (negative) snow depth change from July 2011 until end of 2015. As it can be seen, *SNOWPACK* currently underestimates both snow accumulation and ablation throughout the simulation period (in the order of 1.2 cm/day). The underestimation of snow accumulation might be related to an underestimation of precipitation at the wind-prone summit of Hoher Sonnblick while the main period of ablation is well represented by *SNOWPACK*. However, the reasons for the errors are yet not investigated and will be subject to subsequent research.

3. Future collaboration and foreseen publications

From our perspective, the expected benefits of the cooperation with WSL/SLF during the STSM are manifold. On the one hand, we will considerably profit from the extensive experience of WSL/SLF concerning *SNOWPACK* and its application to permafrost modeling. On the other hand, the permafrost modeling approach is part of the larger and longer-term *ATMOperm* project (*Atmosphere-permafrost relationship in the Austrian Alps* funded by the Austrian Academy of Sciences) which also aims at setting up a permanent permafrost monitoring based on geophysical methods. Therefore, we will be able to comprehensibly evaluate *SNOWPACK* in terms of the ground thermal regime and expect to contribute to future model developments.

Based on the study of Luetschg et al. (2008), we will set up a sensitivity study together with WSL/SLF focusing on snow-relevant processes, in order to determine the most important factors driving the ground thermal regime. Furthermore, we will investigate the added-value of high quality snow height measurements at Hoher Sonnblick derived from laser sensors and evaluate how errors concerning snow heights further translate into estimates of the ground thermal regime. Overall, we expect a contribution to WG3 from the planned investigations presented above by a detailed sensitivity and uncertainty analysis of the role of snow cover and its physical properties in terms of permafrost degradation in high-alpine areas.

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