Modeling Mountain Permafrost Distribution: A New Permafrost Map of Austria

Barbara Ebohon
Department of Geography and Geology, University of Salzburg, Austria
Lothar Schrott
Department of Geography and Geology, University of Salzburg, Austria

Abstract

Alpine permafrost response is very sensitive to climate change. Thus, it is of great interest to estimate and assess permafrost distribution in high mountain areas. In this study, the permafrost distribution of the Austrian Alps was modeled by using commands of the programs PERMAKART (for steep slopes) and PERM (for footslope-positions) which were applied in a DTM with a resolution of 50 m. Possible and probable permafrost areas of the Austrian Alps comprise approximately 1600 km². The potential permafrost area has been compared with BTS, spring temperature measurements, alpine meadows, and isotherms of the MAAT (mean annual air temperature). The results of the validation show that the map still needs some improvement on a local scale, but simulates the possible and probable permafrost distribution of the Austrian Alps as a good general overview.

Keywords: alpine permafrost; Austrian Alps; simulation; validation.

Introduction

Several studies carried out in the Austrian Alps have shown permafrost distribution above approximately 2500 m a.s.l. (Lieb 1998). Current global warming already causes a degradation of permafrost in some mountain regions.

Of particular interest are areas with discontinuous permafrost on steep talus slopes and rock walls. Due to the absence of a blocky layer, rock faces react quickly to climate change compared with debris-covered slopes (Gruber et al. 2004, Mittaz et al. 2000). In densely populated and developed mountain areas (e.g., ski resorts, etc.), where a degradation of permafrost, in particular at its lower limit could cause enhanced debris flow and rockfall activity, mapping and modeling of permafrost distribution is an important prerequisite to prevent natural hazards and risks.

In Switzerland, Haeberli has already started to publish profound knowledge about permafrost distribution in the year 1975. Afterwards a lot of empirical models were developed (e.g., PERMAKART: Keller 1992, PERMAMAP: Hoelzle 1994, PERM: Imhof 1996, PERMAMOD: Frauenfelder 1998). Now, also complex process-oriented models (e.g., PERMEBAL: Stocker-Mittaz et al. 2002), which are based on the particular understanding of the energy fluxes between permafrost and the atmosphere (Hoelzle et al. 2001, Etzelmueller et al. 2001), are already available. However, until recently, the possible and probable permafrost distribution in Austria has been mapped and modeled for only a few local regions (e.g., parts of the High and Low Tauern range) (Lieb 1996, Lieb 1998, Kellerer-Pirklbauer 2005).

Compared to Switzerland, Austria has much less direct (e.g., BTS, geophysics) and indirect data of permafrost occurrence; therefore, modeling of permafrost distribution is just slightly developing.

The aim of this study is to model the permafrost distribution for the entire Austrian Alps by adjusted lower limits for possible and probable permafrost with a simple model considering the relation between slope, altitude, aspect, and permafrost occurrence. In this approach, the often-used trisection of sporadic (<30%), discontinuous (30–80%) and continuous (>80%) permafrost (Nyenhuis 2006) is applied, where sporadic equals possible and discontinuous equals probable permafrost.

Table 1. Values used for the simulation.

	Permafrost possible (sporadic)		Permafrost probable (discontinuous)	
	Steep Slopes	Foot-slope positions	Steep Slopes	Foot-slope positions
N	2300 m a.s.l.	1690 m a.s.l.	2500 m a.s.l.	2410m a.s.l.
NE	2450 m a.s.l.	2100 m a.s.l.	2600 m a.s.l.	2500m a.s.l.
E	2575 m a.s.l.	2220 m a.s.l.	2720 m a.s.l.	2520m a.s.l.
SE	2700 m a.s.l.	2230 m a.s.l.	2850 m a.s.l.	2630m a.s.l.
S	2900 m a.s.l.	2340 m a.s.l.	2900 m a.s.l.	2690m a.s.l.
SW	2650 m a.s.l.	2230 m a.s.l.	2850 m a.s.l.	2630m a.s.l.
W	2600 m a.s.l.	2160 m a.s.l.	2700 m a.s.l.	2510m a.s.l.
NW	2530 m a.s.l.	2120 m a.s.l.	2580 m a.s.l.	2470m a.s.l.
Flat areas	Permafrost possible (sporadic)		Permafrost probable (discontinuous)	
Wind-exposed	2590m a.s.l.		2710m a.s.l.	
Sheltered from wind	2640m a.s.l.		2900m a.s.l.	

Although such a map has, inherently, a limited accuracy, it allows approximations of the permafrost distribution on a national scale and enables comparisons with other Alpine provinces and countries (Frauenfelder et al. 1998).

Austria is positioned at the edge of the eastern margin of the Alps. The absolute heights of mountain ranges decline from west to east in Austria, so that the permafrost areas have their maximum extension in the western federal states.

Methods

The first well-known permafrost model in Central Europe, known as PERMAKART, has been introduced by Keller (1992). PERMAKART is implemented into the GIS-software ARC INFO. On the basis of the topo-climatic key from Heaberli (1975), which analyses the relation between slope, altitude, aspect, and permafrost occurrence, the model is able to distinguish between probable, possible, and no permafrost.

The model PERM (Imhof 1996) is also mostly based on the topo-climatic key from Heaberli (1975), but has been implemented into the raster-GIS-system IDRISI. For the calculation of the foot-slope positions, the differentiating GIS-System didn't offer the same possibilities as ARC VIEW. Therefore, foot-slope positions are generated manually through a smoothing of the DTM.

To work in detectible paces, every step was reproduced in ArcGIS9. Since the empirical values for the simulation (limits of possible and probable permafrost distribution related to altitude, aspect, slope- and footslope-positions) were originally deduced and calibrated for the Upper Engadine in the eastern Swiss Alps (Haeberli 1975), it was necessary to adjust them to the eastern Alps. Values of the lower limits of discontinuous permafrost in the central Alps of Austria were used after Lieb (1998) to model the probable permafrost distribution. Since values for the lower limit of possible permafrost were not available, they have been deduced from the relation between lower limits of possible to probable permafrost in Switzerland.

For the calculation of the lower limit of permafrost for wind-exposed areas, mean elevation values of steep slopes are generated for probable and possible permafrost. Concerning regions of possible permafrost, the lower limit for wind-sheltered areas lays 50 m above the one for wind exposed regions. For wind-sheltered areas, the highest value (2900 m a.s.l.) is used to determine the lower boundary of probable permafrost.

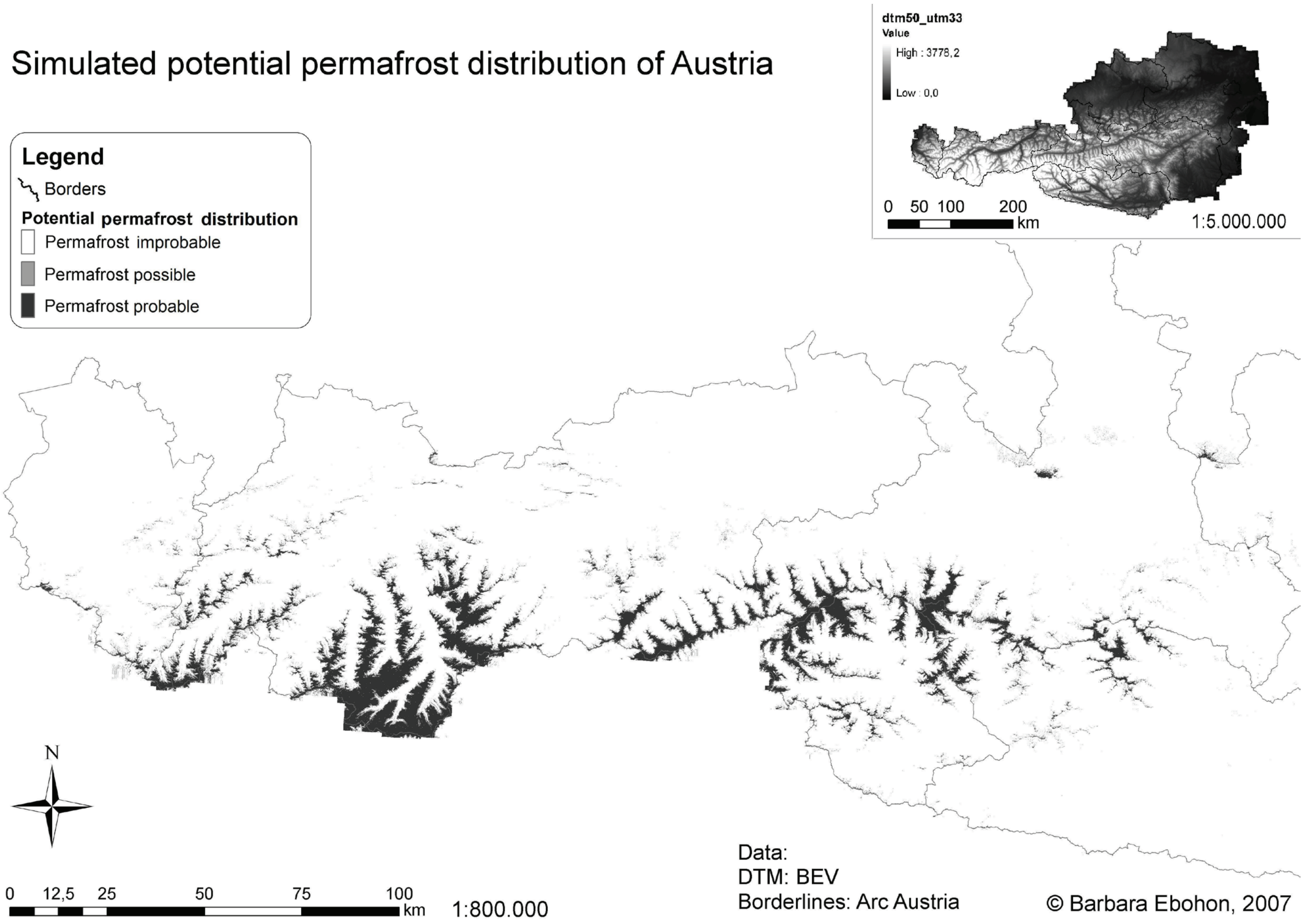

Figure 1. Map of the permafrost distribution of Austria showing the total permafrost territory of about 1600 km² (The difference between possible and probable permafrost can not be seen in this resolution: for higher resolution please see Figs. 5 and 6.).

Previous studies using PERMAKART and PERM show that this application of permafrost modeling, utilized on a nationwide scale, allows good approximations of permafrost distribution.

In a first approach, queries similar to the model PERMAKART (Keller 1994) were used to simulate permafrost of steep slopes. A map of inclination was produced and utilized to highlight all areas above the limits of possible and probable permafrost steeper than 10°, subdivided into different aspects.

The footslope-positions were worked out through a calculation of the curvature similar to the model PERM (Imhof 1992): First the DTM was smoothed, and then the original DTM was subtracted from the smoothed DTM. Areas which show values above zero are supposed to be convex regions, while all values below zero show concavities. In a next step, a map which pointed out all regions flatter than 10° was produced. This step allowed determining all flat and concave areas.

Afterwards all areas steeper than 10° were extracted and hemmed with a 150 m buffer. Following those queries, areas could be extracted which are concave, flat, and not more than 150 m away from steep slopes. On these footslope-positions the values for possible and probable permafrost were applied.

In this context, Haeberli (1975) and Etzelmueller (2001) stated that, in flat areas, the influence of air temperature is much more important than differences in radiation. Following that, flat, concave (troughs), and convex (domes) areas with less than 10° inclination above the lower limit of possible and probable permafrost were pictured.

All queries were summed and applied on a DTM with a resolution of 50 m using the UTM-coordinate system.

Table 2. Comparison of the results from the model starting to calculate steep slopes at 5° and at 10° inclination.

	5°model	10° model
Permafrost possible	711 km²	721 km²
Permafrost probable	899 km²	873 km²
Permafrost distribution (total)	1610 km²	1594 km²

Table 3: Relative permafrost areas of Austria (%) by federal states.

	Permafrost total	Permafrost possible	Permafrost probable
Burgenland	0.00	0.00	0.00
Carinthia	1.65	0.87	0.78
Lower Austria	0.00	0.00	0.00
Upper Austria	0.04	0.03	0.01
Salzburg	2.76	1.48	1.28
Styria	0.05	0.05	0.00
Tirol	9.28	3.84	5.44
Vorarlberg	1.90	1.28	0.61
Vienna	0.00	0.00	0.00
Austria	1.90	0.86	1.04

Results and Validation

Results

The permafrost map displays areas with improbable (equals no permafrost), possible, and probable permafrost and gives an overview of regional differences. At first sight, there is a strong dominance of permafrost occurrence in the western higher part of Austria, whereas the eastern part shows a somewhat patchy distribution.

To pay attention to different inclination thresholds discussed in the literature (5°/10°), two models with different conditions were applied. It is surprising that there are hardly differences in the calculated permafrost areas between the model which started calculating steep slopes at 5° inclination and the second one taking 10° into consideration. In the calculations that follow, the results of the 10° model were used.

Modeling results show that 1.9% of the territory of Austria can be assigned to mountain permafrost. This corresponds to an area of approximately 1600 km².

In Tyrol, 9.3% of the area is underlain by permafrost. This is a significant proportion compared to values for Switzerland (between 4 and 6%). Estimates for Salzburg, Vorarlberg, and Carinthia vary between 2 and 3%.

Validation

Validation was primarily a comparing of the modeling results with data from basal snow temperature measurements (BTS) and spring water temperatures.

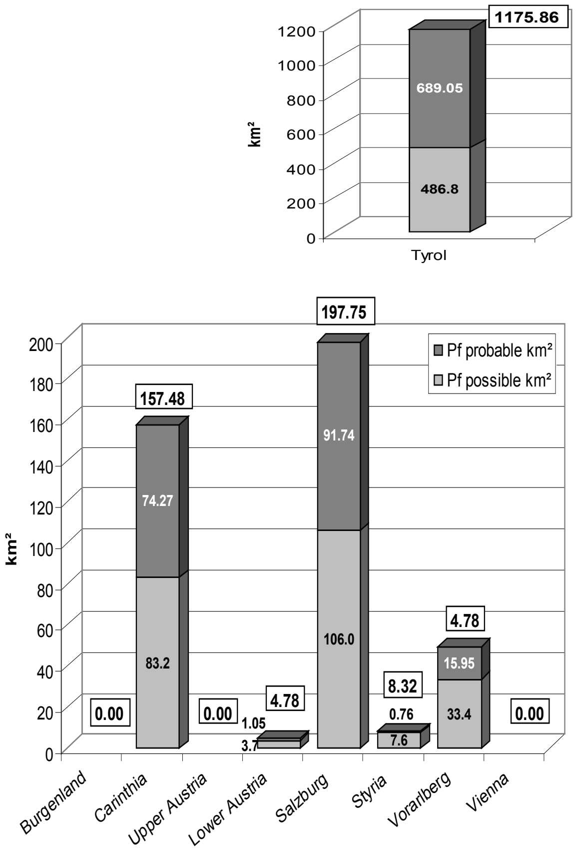

Figure 2a, 2b. Potential permafrost distribution of Austria in km².

Summarizing all measurements from local study sites such as Kaisergratspitz, Oelgrube, Sulzkar, Goessnitzvalley/Langvalley, Hoher Sonnblick, Doesener Valley, Reisseck, and Hafergruppe, data from 300 point measurements allow a quick and reasonably good approximation of regional permafrost distribution.

Following the comparison between the simulated area with the measuring points, 48.7% of the measurements (BTS, spring water temperatures) match the three simulated categories (no PF, possible PF, probable PF). However, it should be noted that many points are just slightly outside the simulated permafrost area and probably a problem of DTM resolution or imprecise information of the point measurements which were mostly analogue and subsequently digitized for the validation. Combining the two categories, "PF possible" and "PF probable," into one entire zone, already 71.1% of the point measurements (BTS and spring water temperature data) used for validation accord with this calculation. Zoning the area of simulated permafrost after different exposures, it should be stated that N, NE, and SE are mapped well, and E, S, and SW are relatively well-presented. W and NW need further investigation on a local scale.

It can also be mentioned, that areas of rockslopes without vegetation, extracted from CORINE-Data 2000 (Aubrecht 1998), often match the modeled areas of permafrost.

Comparing the simulated permafrost area with the distribution of alpine meadows (CORINE 2000), only about 3% (44.5 km²) of simulated potential permafrost distribution intersects with them (Fig. 5). It has to be considered that permafrost and vegetation exclude each other often, but not always. It is notable that most intersections are northerly exposures. Therefore, northern aspects should be investigated more precisely on a local scale (e.g., grain size analyses, lithology, etc.).

It is well known that permafrost probably exists above certain threshold values concerning the MAAT (mean annual air temperature). Following this approach, another adjustment is made through the comparison of simulated permafrost areas with calculated isotherms based on MAAT from 1961–1990 and a total of 117 measurement stations and contour lines. The calculated isotherms mostly lay some few meters above the contour lines applied by Lieb (1996), who used the threshold of 2250 m a.s.l. for discontinuous permafrost and 3250 m a.s.l. for continuous permafrost. Comparatively, areas above the -2°C isotherm refer to discontinuous permafrost, while areas above the -6°C isotherm point to continuous permafrost. It must be stated, that only a small zone of continuous permafrost can be expected in Austria because most of the areas above -6°C MAAT are occupied by glaciers. In the N, NW, and NE aspects, the borderlines of discontinuous permafrost match the modeled area quite well, while in the SW, S, and SE aspects, borderlines are much lower than the limit of simulated permafrost.

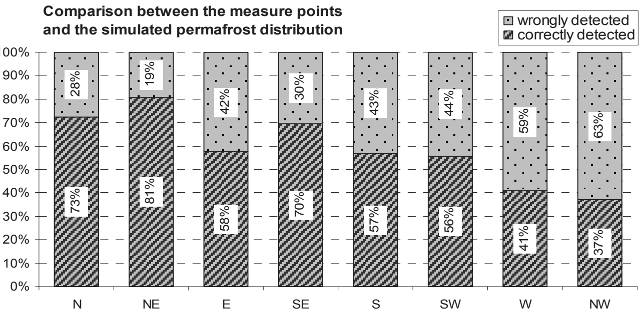

Figure 3. Comparison between measurement points (BTS, spring water temperatures) and permafrost occurrence (simulated permafrost distribution), differentiated in aspects.

Discussion

In summary, the simulation gives a useful overview of possible and probable permafrost distribution in the Austrian Alps. There are, however, still some unsolved problems and inaccuracies. As Keller & Hoelzle (1996) stated, one big issue is the appointment of the critical inclination, which differentiates between steep and moderate slopes. The approach presented has shown that there are minor differences between the permafrost areas calculated with the two models (5 and 10° inclination), but it remains unclear whether a threshold above 10° would show better results.

Also, the distinction between western and eastern Austria should be analyzed in more detail according to well-known temperature differences.

Improvements to this study would also be achieved by including more data on rock glaciers and higher resolution DTM data to better represent the strongly differentiated relief of the Austrian Alps.

Moreover, the distinction between the two categories—"permafrost possible" and "permafrost probable"—is still problematic because the data used on existing permafrost occurrences are based on point measurements (BTS and spring temperatures) only. The interpolation of these data produces simulated lower boundaries of permafrost distribution with limited accuracy. A further problem is related to the semantic differentiation of possible and probable permafrost, and to the unknown quantitative proportion of permafrost in these categories (Heginbottom 2002).

There are also problems with the values used themselves: they represent only mean values derived from one region in the Upper Tauern. Because of a lack of values for other areas, they were used to model the permafrost distribution for the entire area of Austria.

To improve the accuracy of the regional permafrost distribution map, more validation data from BTS measurements and field geophysics are needed. Furthermore, data should be more uniformly distributed over the Austrian territory.

It would then be possible to rework the empirical approach and to derive values for permafrost distribution. The more empirical data available, the better the adjustment to regional and local conditions would be.

Lieb (1996) stated that the difference between N and S orientation concerning intact rock glaciers is about 273 m (mean value for entire Austria). Whether the accuracy can be raised by adjusting the permafrost boundaries to this value is still an open question.

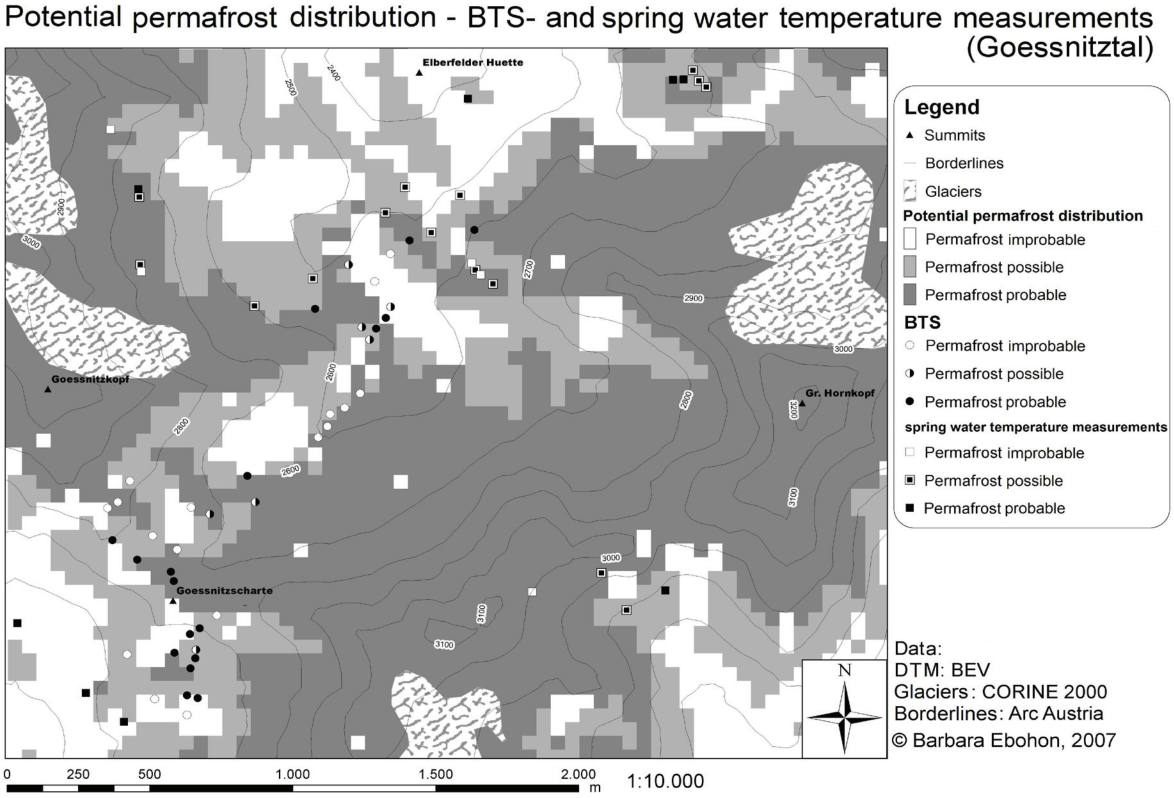

Figure 4. Permafrost distribution compared with BTS data and spring temperature measurements (data: G.K. Lieb, pers.com.).

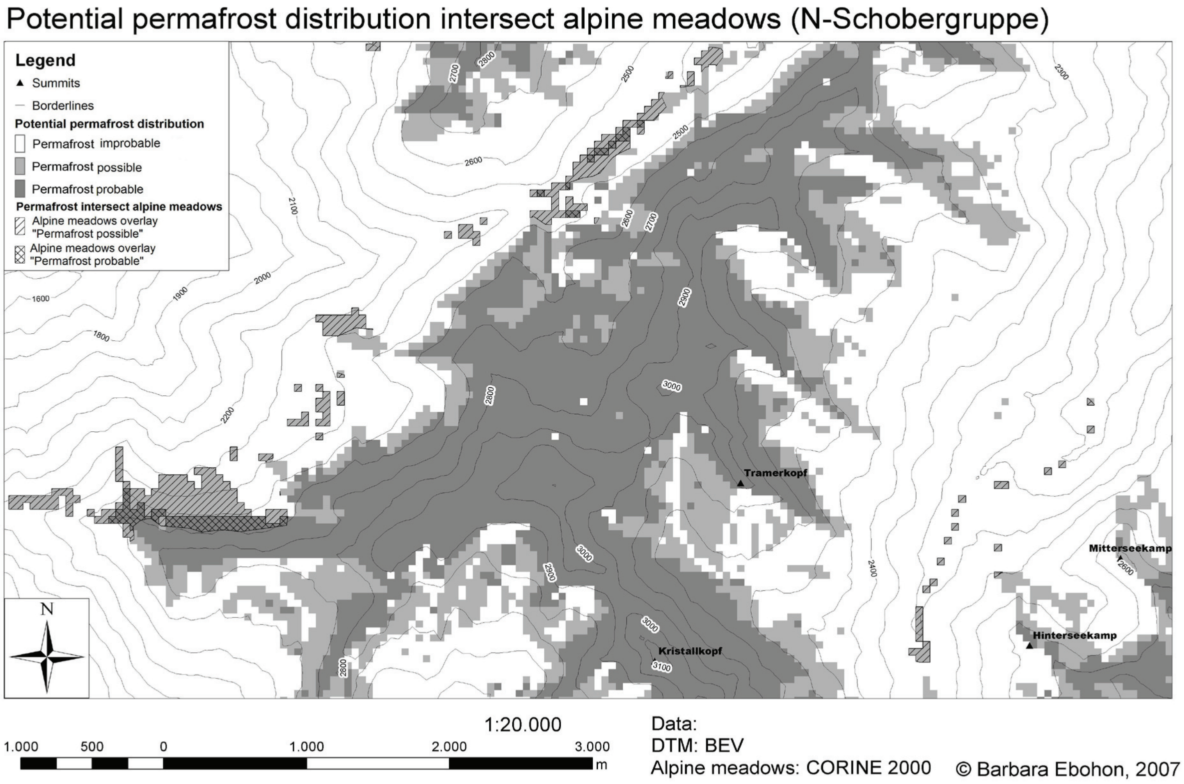

Figure 5. Comparison of simulated permafrost distribution with vegetation (alpine meadows).

Another important issue is the indication of permafrost areas at lower altitudes than expected, which is probably only possible to be pictured through a physically based model. This kind of model is able to reproduce the energy balance, and therefore, can record those areas and should be further developed in future.

Acknowledgments

We gratefully acknowledge the valuable comments by two anonymous reviewers.

Data were kindly provided by:

- Karl Krainer (University of Innsbruck): data from basal snow temperature measurements (BTS).
- Gerhard Karl Lieb (University of Graz): data from basal snow temperature measurements (BTS) and spring water temperature measurements.
- Wolfgang Schöner (ZAMG): Project PERSON (Permafrost-monitoring Sonnblick) GZ BMLFUW-UW.1.3.2/0528-V/5/2005 by order of Lebensministerium.
- Herbert Formayer (University of Natural resources and Applied Life Sciences, Vienna, Austria): Calculated Isotherms.
- Michael Avian (Graz, University of Technology).
- BEV: DTM.

References

Aubrecht, P. 1998. *CORINE Landcover Österreich. Vom Sattelitenbild zum digitalen Bodenbedeckungssatz*. Wien: Umweltbundesamt Monographien, 93: 59 pp.

Etzelmueller, B., Hoelzle, M., Heggem, E.S.F., Isaksen, K., Mittaz, C., Vonder Muehll, D., Ødegård, R.S., Haeberli, W. & Sollid, J.L. 2001. Mapping and modelling the occurrence and distribution of mountain permafrost. *Norwegian Journal of Geography* 55(4): 186-194.

Frauenfelder, R., Allgöwer, B., Haeberli, W. & Hoelzle, M. 1998. Permafrost investigations with GIS – a case study in the Fletschhorn area, Wallis, Swiss Alps. *Proceedings of the 7th International Conference on Permafrost, Yellowknife, Canada, June 23–27, 1998*: 291-295.

Gruber, S., Hoelzle, M. & Haeberli, W. 2004. Rock wall temperatures in the Alps: Modelling their topographic distribution and regional differences. *Permafrost and Periglacial Processes* 15(3): 299-307.

Haeberli, W. 1975. *Untersuchungen zur Verbreitung von Permafrost zwischen Flüelapass und Piz Grialetsch (Graubünden)*. Zürich: Mitteilung der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich, 17: 182 pp.

Heginbottom, J.A. 2002. Permafrost mapping: a review. *Progress in Physical Geography* 26(4): 623-642.

Hoelzle, M. 1994. *Permafrost und Gletscher im Oberengadin—Grundlagen und Anwendungsbeispiele für automatisierte Schätzverfahren*, Zürich: VAW Mitteilung der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich, 132: 121 pp.

Hoelzle, M., Mittaz, C., Etzelmller, B. & Haeberli, W. 2001. Surface energy fluxes and distribution models of permafrost in European mountain areas: an overview of current developments. *Permafrost and Periglacial Processes* 12(1): 53-68.

Imhof, M. 1996. PERM – ein Programm für die automatische Kartierung von Permafrost in den Schweizer Alpen. In: W. Haeberli, M. Hölzle, J.P. Dousse, J.M. Gardaz, M. Imhof, F. Keller, P. Kunz, R. Lugon & E. Reynard, *Simulation der Permafrostverbreitung in den Alpen mit geographischen Informationssystemen. Arbeitsbericht NFP 31.* Zürich: vdf Hochschulverlag, 15-34.

Keller, F. 1992. Automated mapping of mountain permafrost using the program PERMAKART within the geographical information system ARC/INFO. *Permafrost and Periglacial Processes* 3(2): 133-138.

Keller, F. 1994. *Interaktionen zwischen Schnee und Permafrost. Eine Grundlagenstudie im Oberengadin*. Zürich: Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich, 127: 145 pp.

Keller, F & Hölzle, M. 1996. PERMAKART und PERMAMAP. In: W. Haeberli, M. Hölzle, J.P. Dousse, J.M. Gardaz, M. Imhof, F. Keller, P. Kunz R. Lugon, & E. Reynard, *Simulation der Permafrostverbreitung in den Alpen mit geographischen Informationssystemen, Arbeitsbericht NFP 31*. Zürich: vdf Hochschulverlag, 35-46.

Kellerer-Pirklbauer, A. 2005. Alpine permafrost occurrence at its spatial limits: First results from the eastern margin of the European Alps. *Norwegian Journal of Geography* 59: 184-193.

Lieb, G.K. 2007. personal comment (29.1.2007).

Lieb, G.K. 1996. *Beiträge zur Permafrostforschung in Österreich*. Arbeiten aus dem Institut für Geographie der Karl-Franzens-Universität Graz, 33: 223 pp.

Lieb, G.K. 1998. High-Mountain permafrost in the Austrian Alps (Europe). *Proceedings of the 7th International Conference on Permafrost, Yellowknife, Canada, June 23–27, 1998*: 663-668.

Mittaz, C., Hoelzle, M. & Haeberli, W. 2000. First results and interpretation of energy flux measurements over alpine permafrost. *Annals of Glaciology* 31: 275-280.

Nyenhuis, M. 2006. *Permafrost und Sedimenthaushalt in einem alpinen Geosystem.* Bonn: Bonner Geographische Abhandlungen 116: 142 pp.

Stocker-Mittaz, C., Hoelze, M. & Haeberli, W. 2002. Modelling alpine permafrost distribution based on energy-balance data: a first step. *Permafrost and Periglacial Processes* 13(4): 271-282.