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Modelling of potential permafrost distribution during the Younger Dryas, the Little Ice Age and at present in the Reisseck Mountains, Hohe Tauern Range, Austria

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Younger Dryas
Austria

Abstract

Regions with marginal occurrence of discontinuous permafrost are very specific due their transition to non-permafrost conditions at recent times. Knowledge about the potential distribution of permafrost in the past and at present is crucial to understand its characteristics and dynamics as well as inherent processes. This analysis comprises the simulation of the potential distribution of discontinuous permafrost using six scenarios with different temperature depressions in the entire Reisseck Mountains (46°57'N, 13°22'E) for the year 2000 (*Sc-2000*), the Little Ice Age (*Sc-LIA*) and four scenarios for the Younger Dryas – locally referred to as Egesen – in the Alpine Lateglacial period (*Sc-E1* to *Sc-E4*). The results were validated at two different spatial scales; at a regional scale for the entire study region Reisseck Mountains, Central Austria, with data from the distribution of relict and intact rock glaciers; at a local scale for the study area Hintereggengraben Valley – Hohe Leier with data from five years of continuous ground temperature monitoring using data from eight automatic miniature temperature dataloggers. Past conditions were simulated using the year 2000 as a basis for the lower limits of permafrost occurrence. A depression in the mean annual temperature of -1.4 K was used for modelling permafrost conditions during the LIA. Potential permafrost distribution in the Younger Dryas was modelled with temperature depression of -2.5 to -4.0 K compared to the LIA. Our results show a spatial distribution of 9.94 km² (3.1 %) in the scenario 2000 to 134.57 km² (42.1 %) in the scenario *Sc-E4*. The simulations of the thermal conditions in the Younger Dryas validated with the locations of the relict rock glacier suggest scenario *Sc-E1* as the most probable. This implies a mean annual temperature depression of -2.5 K compared to LIA and depression of the lower limit of permafrost of ca. -560 m compared to the year 2000. A few relict rock glaciers are located in much lower areas and can therefore be stated as formed in pre-Egesen stages. As a further palaeoclimatical consequence we assume that all inactive rock glaciers in the Reisseck Mountains were still active in the LIA.

Hochgebirgsregionen mit geringer Verbreitung von diskontinuierlichem Permafrost sind in der Gegenwart und unter Berücksichtigung des gegenwärtigen Klimawandels sehr bedeutsam hinsichtlich ihrer Veränderung in Richtung Permafrost freien Regionen. Um damit in Zusammenhang stehende Prozesse und deren Dynamik besser verstehen zu können, ist es wichtig, die räumliche Verbreitung von rezenten aber auch ehemaligen Permafrostarealen zu kennen. Diese Studie umfasst die Modellierung der Permafrostverbreitung anhand von sechs verschiedenen Szenarien auf Basis unterschiedlicher Jahresmitteltemperaturdepressionen in der Reisseck-Gruppe (46°57'N, 13°22'E), Hohe Tauern, für das Jahr 2000 (*Sc-2000*), für die der Kleinen Eiszeit ca. um 1850 (*Sc-LIA* und vier Szenarien für die Jüngere Dryas/Egesen im Alpinen Spätglazial (*Sc-E1* bis *Sc-E4*). Die Simulationsergebnisse wurden in zwei Skalenbereichen überprüft: im regionalen Maßstab für die gesamte Reisseck Gruppe mithilfe der Verbreitung von reliktischen und intakten Blockgletschern, im lokalen Maßstab mit Hilfe von Auswertungen von Bodentemperaturdaten gemessen an acht Standpunkten im Arbeitsgebiet Hintereggengraben - Hohe Leier. Die Untergrenzen der Permafrostverbreitung für das Jahr 2000 wurden als Basis für die Modellierung der Bedingungen in der Kleinen Eiszeit bzw. für das Spätglazial verwendet. Als Temperaturdepression relativ zu 2000 wurde für die Kleine Eiszeit -1,4 K angenommen. Weiters wurden Temperaturdepressionswerte von -2,5 bis -4,0 K relativ zur Kleinen Eiszeit für die vier Szenarien in der Jüngere Dryas angenommen. Die Ergebnisse zeigen eine räumliche Verbreitung des diskontinuierlichen Permafrostes von 9,94 km² (3,1 %) im Szenario *Sc-2000* bis 134,57 km² (42,1 %) im Szenario *Sc-E4*. Die Überprüfung dieser Modellergebnisse mithilfe der Lage der reliktischen Blockgletscher lassen das Szenario *Sc-E1* als das wahrscheinlichste für die Verbreitung der meisten im Gebiet vorhandenen reliktischen Blockgletscher erscheinen. Dies bedingt eine Temperaturdepression von -2,5 K im Vergleich zur LIA bzw. eine Depression der Permafrostuntergrenze von ca. -560 m im Vergleich zum Jahr 2000. Einige wenige Blockgletscher liegen in deutlich tiefer gelegenen Arealen und sind somit wahrscheinlich Pre-Egesen zeitlich einzustufen. Als weitere paläoklimatische Schlussfolgerung nehmen wir an, dass alle heute inaktiven Blockgletscher in der Kleinen Eiszeit noch aktiv gewesen waren.

1. Introduction

Extensive areas in the European Alps are at conditions where the ground remains in negative temperatures all year round. These permafrost areas have been under raising attention in science since the mid-1970s (e.g. Haeberli, 1975) because of ist sensitivity to climate change and its impacts in high mountain environments. Many of these permafrost areas are located at the lower altitudinal limit of permafrost occurrence close to thawing conditions. The most prominent indicators for the existence of mountain permafrost are active rock glaciers. Active rock glaciers contain permafrost and are large-scale creep features in permafrost environments consisting of perennially frozen debris material (talus and/or till) supersaturated with interstitial ice and ice lenses (Barsch, 1996). Rock glaciers can be differentiated after Barsch (1996) - amongst others - in terms of activity status as (i) active, (ii) inactive and (iii) relict rock glaciers. Rock glaciers which are relict at present contain no ice, but indicate past permafrost conditions. Furthermore, rock glaciers which contain ice are termed intact rock glaciers, where inactive rock glaciers do not move anymore in contrary to active rock glaciers still moving downslope. The investigation of the evolution of present and past permafrost distribution and related rock glacier formation (during the Alpine Lateglacial and Holocene time periods) is helpful to better understand recent and future processes related to anticipated future permafrost degradation.

In the last 15 years, studies on the present distribution of permafrost have been conducted in many parts of the European Alps. Imhof (1996), for instance, modelled and verified permafrost distribution in the Bernese Alps, Keller et al., (1998) developed the first map of permafrost occurrence of the Swiss Alps, and Ebohon and Schrott (2008) assigned more than 900 km² of the Austria Alps as “permafrost probable” areas based on a regional modelling approach. However, studies on the assessment of potential permafrost distribution in the Lateglacial are rare. Lambiel and Reynard (2001) for instance presented considerations about modelling potential permafrost during the Younger Dryas (referred to Egesen stadial in the European Alps), Little Ice Age (LIA) and at present in the Bagne-Hérémence area, Western Swiss Alps, and Frauenfelder et al. (2001) modelled permafrost distribution during the Younger Dryas in the Err-Julier area, Swiss Alps.

Substantially more research has been carried out in the determination of Lateglacial glacier extent and related equilibrium line altitudes (ELA) of glaciers (e.g. van Husen, 1997; Kerschner and Ivy-Ochs, 2007; Ivy-Ochs et al., 2009). As rock glaciers only develop in unglacierized terrain, the consequence of this deglaciation is the formation of rock glaciers in these areas if permafrost conditions occur. As found out for western Austria, a first major formation period of rock glaciers was after the Egesen maximum, about 11.8 ka BP (Kerschner et al., 2008). Under “Egesen” we understand a sequence of glacier advances in the first part of the Younger Dryas consisting of three different substages Egesen I (= Egesen maximum) to III with the largest glacier extent during Egesen I and the smallest during Egesen III (Sailer and Kerschner, 1999). Kerschner et al. (2008) report that these rock glaciers stabilized after the end of the Younger Dryas (11.0 – 10.5 ka BP). Moreover, Sailer and Kerschner (1999) discuss ELA variations of glaciers in the Ferwall Mountains (Western Austria) in the Younger Dryas. Rock glacier locations in respect to deglaciated areas were subsequently determined and they suggest most of the rock glaciers formed during or after the Egesen II.

Research in areas with marginal permafrost occurrence at present in Central and Eastern Austria are restricted (Lieb and Schopper, 1991; Kellerer-Pirklbauer, 2005) and considerations about palaeo-permafrost distribution are few and mostly related to relict rock glaciers (Nagl, 1976; Lieb, 1996; Kellerer-Pirklbauer et al., 2012). This article aims to contribute to the knowledge about palaeo-permafrost and present distribution in a region of marginal permafrost occurrence at present in a study area located in central Austria. Thereby, we present results from modelling potential permafrost distribution in six different scenarios and the validation of the models using results from monitoring ground thermal conditions and rock glacier distribution.

2. Area of investigation

Our investigation focuses on two different spatial scales related to different methodological approaches; the entire study region comprises the Reisseck Mountains and at a local scale we focussed on the study area Hintereggen Valley-Hohe Leier area (HEG) (Fig. 1). The Reisseck Mountains comprise the SE-most part of the Hohe Tauern Range being part of the Austrian Central Alps. The study region covers an area of ca. 320 km² and reaches its highest point at the Grosses Reißeck (2965 m a.s.l., Fig.1). The study area Hintereggengraben Valley – Hohe Leier covers 16.2 km². The highest point of HEG is the Hohe Leier with 2774 m a.s.l. HEG forms the SE part of the Reisseck Mountains. Mean annual air temperature was -0.25° C (period 1961 – 2006), measured at the meteorological station Reisseckhütte, located at 2287 m a.s.l. and 900m NW of the Rossalmscharte (Taucher, 2010). The main ridge of the Central Austrian Alps prevents this region from the supply of wet air masses from NW resulting in a relatively low mean annual precipitation of 1265 mm (period 1961 – 2006) at the Reisseckhütte (Taucher, 2010).

In 2006, the study area HEG became a major study site of the project “ALPCHANGE – Climate Change and Impacts in Southern Austrian Alpine Regions” with a project running period of 2006 – 2011. The main objective of ALPCHANGE was to quantify landscape dynamics in Alpine regions caused by climate change in past and present. Within ALPCHANGE, analyses of the signals from various dynamic landscape parameters – permafrost, geomorphodynamics, glaciers, and snow – were carried out by a series of different methods.

Apart from the northernmost fringe of the Reisseck Mountains named Dösen Valley (e.g. Kaufmann and Ladstädter, 2007) the Reisseck Mountains are a rather nameless area in terms of published scientific permafrost and periglacial research (e.g. Lieb, 1996; Avian, 2003; Kellerer-Pirklbauer, 2008). However, one important article about permafrost in the Central Reisseck Mountains was published by Krobath and Lieb (2002) using permafrost modelling and permafrost field evidences in two small cirques. Furthermore, Schaffhauser

(1971) was the first who recognized ice-rich debris accumulations in the study region. Within ALPCHANGE several follow-up studies were conducted with relation to the Reisseck Mountains. Taucher et al. (2009) analysed monthly values of four different climatic elements from 44 meteorological stations to quantify climatic trends over a 46 year period (1961-2006) at six high-altitude areas including HEG. Lastly, Nutz et al. (2009) analysed surface characteristics of HEG and six other valley heads in respect to permafrost distribution.

Additional unpublished research related to permafrost was carried out mostly in the central part of the Reisseck Mountains around the Reisseck Hütte (Mühlgraben Valley): (i) spring temperature measurements (n = 19, M. Krobath: September 1994 and June 2000), and (ii) test measurements of DC-resistivity E of Riedbock (Austrian Geological Survey, GBA, Juli 2001).

3. Method and data basis

3.1 Modelling potential distribution of discontinuous permafrost

The very first attempts to estimate the potential permafrost distribution in the Alps were done in the Swiss Alps formulating some "rules of thumbs" for the prediction of mountain permafrost bin the Alps (Haeberli, 1975). Some parts of these "rules of thumbs" were implemented in the program "PERMAKART" by Keller (1992) using empirical-statistical models directly related to topoclimatic factors (altitude, slope and aspect, mean air temperature and solar radiation) and information about the influence of avalanche deposit areas in slope foot areas. Later, Ebohon and Schrott (2008) used PERMAKART for the estimation of the potential permafrost distribution in the Austrian Alps. More complex and process oriented models focussing on detailed understanding of atmosphere-permafrost energy fluxes were presented by Stocker-Mittaz et al. (2002) using a model called PERMEBAL. Since then, permafrost modelling advanced substantially to a complex field of research (Riseborough et al., 2008), covering not just regions but the entire European Alps (Boeckli et al., 2012) or even the entire globe (Gruber, 2012) with one methodological approach.

In this study, we use an adaptation of PERMAKART for modelling potential permafrost distribution for two reasons. First, only few input parameters are needed. This simplification allows modelling in areas with a lack of area-wide field data. Second, the adjustment to the local situation can be done by simply using the different lower limits of permafrost occurrence. The lower limit of permafrost is based on Lieb (1998) using primarily the lower limit of intact rock glaciers in the Hohe Tauern Range. The model PERMAKART itself considers areas

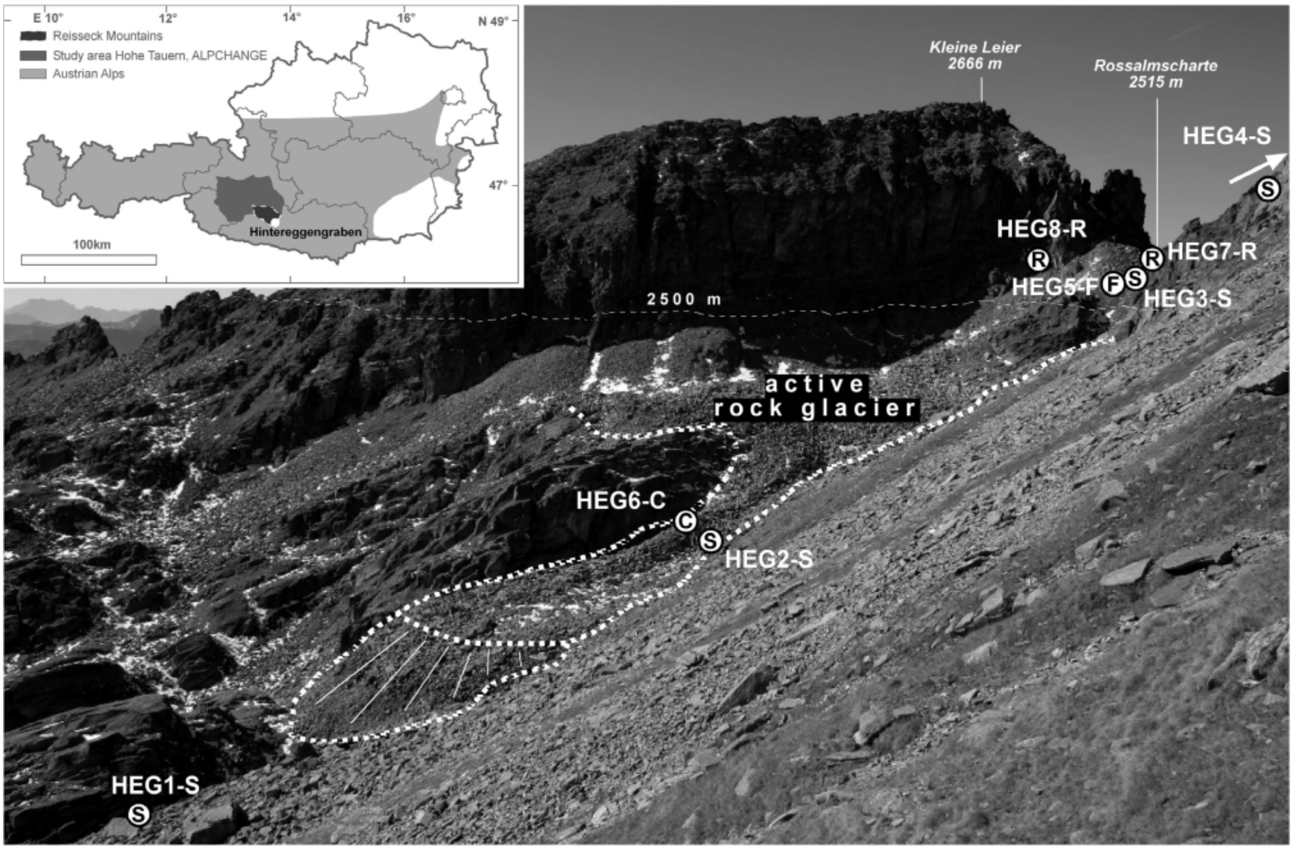


Figure 1: The valley head of study area Hintereggen Valley- Hohe Leier (HEG) showing main landforms and temperature sensor sites with respect to surface conditions: S=surface measurement site; C=coarse-debris site, F=fine-grained site; R=rock wall site. Dotted line indicates margin of the rock glacier. Insert maps shows location of the project area of the ALPCHANGE project within Austria, the study region Reisseck Mountains as well as the local study area HEG.

		Different modelling scenarios					
		Sc-2000	Sc-LIA	Sc-E1	Sc-E2	Sc-E3	Sc-E4
Aspect	Δt	0 (basis)	-1.4 K	-2.5 K	-3.0 K	-3.5 K	-4.0 K
N		2500	2280	1900	1825	1745	1670
NE		2600	2380	2000	1925	1845	1750
E		2720	2500	2120	2045	1965	1890
SE		2850	2630	2250	2175	2095	2020
S		2900	2680	2300	2225	2145	2070
SW		2850	2630	2250	2175	2095	2020
W		2700	2480	2100	2025	1945	1870
NW		2580	2360	1980	1905	1825	1750
Median [m]		2570	2365	2010	1940	1865	1790

Table 1: (a) Simulation input parameters for the lower limit of potential discontinuous permafrost [m a.s.l.] in respect to aspect situation for slopes. (b) Bottom: The median of all scenarios was calculated at the base of all lowest cells [m a.s.l.] of the respective model output (distribution of discontinuous permafrost).

of avalanche accumulation and footslopes but processes like for instance redistribution of snow cover due to wind redistribution, grain size, or advection in coarse substrate are not considered.

The lower limits of potential occurrence of discontinuous permafrost in respect to aspect were calculated using a vertical temperature lapse rate. Table 1 gives an overview of all lapse rates and parameters used in this study. A vertical temperature lapse rate of 6.34 K km^{-1} was calculated for the scenario Sc-LIA and is based on air temperature data from 15 stations in the region during the period 1961–2006 (Taucher et al., 2009). For all the scenarios in the Younger Dryas (*Sc-E1* to *Sc-E4*) we chose the international standard atmospheric lapse rate of 6.50 K km^{-1}. The value of temperature depression for the Sc-LIA relative to today was chosen with -1.4 K based on the studies of Böhm (2006) compared to *Sc-2000*. This lapse rate was calculated from summer temperatures (June-August) from HISTALP database using temperature analyses of 242 sites (mean from high elevation bands across the Greater Alpine Region).

For the estimation of the potential occurrence of permafrost after the last glacier maximum in the Egesen I of the Younger Dryas period, different temperature depression values were used due to following considerations: Sailer and Kerschner (1999) report that relative to the LIA the equilibrium line altitude (ELA) of glaciers in the Ferwall area (Western Tyrol) showed a depression of 290-320 m (Egesen I), 190-230 m (Egesen II) and 120-160 m (Egesen III). In some cirques which were glaciated during the Egesen I (e.g. Ivy-Ochs et al., 2006) rock glaciers moved into the deglaciated areas afterwards. Considering the lower limits of active and relict rock glaciers, Sailer and Kerschner (1999) state a temperature depression of Δt = -4.0 to Δt = -4.5 K. Kerschner and Ivy-Ochs (2007) used different summer temperature scenarios to model ELA-variations in the Younger Dryas which ranged from Δt_s = -3.5 K for interior valleys to Δt_s = -5.0 K at the northern fringe of the Austrian Alps. The small amount of rock glaciers in our study region (31 relict and 19 intact) is not suitable for a substantial statistical analysis of lowest elevation of rock glaciers in respect to aspect and activity status.

The calculation of the potential permafrost occurrence was conducted in the program Arc-Info using the official Austrian DTM as input data with a geometric resolution of 25 m (provided by the Federal Office for Metrology and Surveying (BEV)). We calculated two scenarios in the Holocene and four in the Lateglacial period.

In order to avoid confusion in using model terms in contrast to Lateglacial periods (e.g. Egesen I-III) as well as Holocene glacier stages (e.g. LIA) we indicated the modelled scenarios as follows: scenario at year 2000 as *Sc-2000*, scenario during the LIA (~1850 in the European Alps) as *Sc-LIA*, and the four different scenarios for the Egesen as *Sc-E1* to *Sc-E4*.

For the Holocene we determined the spatial distribution of permafrost for *Sc-2000*, and *Sc-LIA* with a temperature depression of Δt = -1.4 K compared to 2000. In order to get a picture of the potential Lateglacial spatial distribution of permafrost we introduced four scenarios in the Younger Dryas at the base of Kerschner et al. (2008).

These scenarious represent spatial distributions of permafrost with temperature depressions (*Δt*) of (i) *Sc-E1* = -2.5 K, (ii) *Sc-E2* =-3.0 K, (iii) *Sc-E3* = -3.5 K, and (iv) *Sc-E4* =-4.0 K compared to LIA. We choose four scenarios in order to compare different distribution patterns with the altitudinal location of the rock glaciers to deduce the age of the rock glaciers. Table 1 lists the input parameters of all respective scenarios. Furthermore we neglected the fact that lapse rates can occur with possible spatial variations. All model results were filtered spatially and in terms of dimension (threshold: 1.5 x 1.5 pixels (37.5 x 37.5 m) to eliminate simulation artefacts. As a final step all connected cells were subsumed to the term “potential discontinuous permafrost", all isolated cells to the term "potential sporadic permafrost", respectively. To calculate the lower limit of each simulated discontinuous permafrost distribution, all lowest cells in terms of altitude were isolated and statistically analysed (Tab.1, bottom).

3.2 Geomorphological mapping

Knowledge about the distribution of glacial and periglacial landforms gives information about recent and palaeo-climatic situations in certain altitudinal belts. The morphological situation at the study area HEG was mapped visually in two different scales using orthophotographs from the year 2006 with a geometric resolution of 1.0 m provided by the Hohe Tauern National Park administration. At a regional scale, our mapping was strongly linked on the rock glacier inventory developed by Lieb et al. (2010) and comprehensively described by Kellerer-Pirklbauer et al. (2012) for the Eastern Austrian Alps. This inventory differentiates between relict and intact rock glaciers using a minimum mapping unit (MMU) of 1.0 ha and provides therefore useful basic information for our modelling verification. The rock glacier distribution of the entire Reisseck area itself was mapped using a MMU of 1.0 ha to represent the periglacial situation more detailed. At a local scale regarding the valley head of HEG, all glacial and periglacial landforms were mapped with a MMU of 0.1 ha.

3.3 Ground temperature monitoring and analysis

Ground surface and near-surface temperature is continuously monitored at the study area HEG since September 2006. For the present study, ground surface (GST) and near surface ground temperature (GT) data from miniature temperature datalogger (MTD) were used from eight different sites, Figure 2 shows some visual examples of MTD sites during and after instrumentation. Thereby, GST is defined as the surface or near-surface temperature of the ground (bedrock or surficial deposit), measured in the uppermost centimetres (≤3 cm) of the ground. GT is the temperature at an indicated depth. Table 2 gives an overview and data availability of the eight MTD locations. At four sites, only GST was monitored. These four sites (HEG1-S to HEG4-S) were equipped with 1-channel MTDs with one temperature sensor (GeoPrecision, Model M-Log1). At each of the four sites the temperature sensors were located at the ground surface sheltered from direct solar radiation by a thin platy rock still allowing unhampered air circulation. According to Geoprecision, the used PT1000 temperature

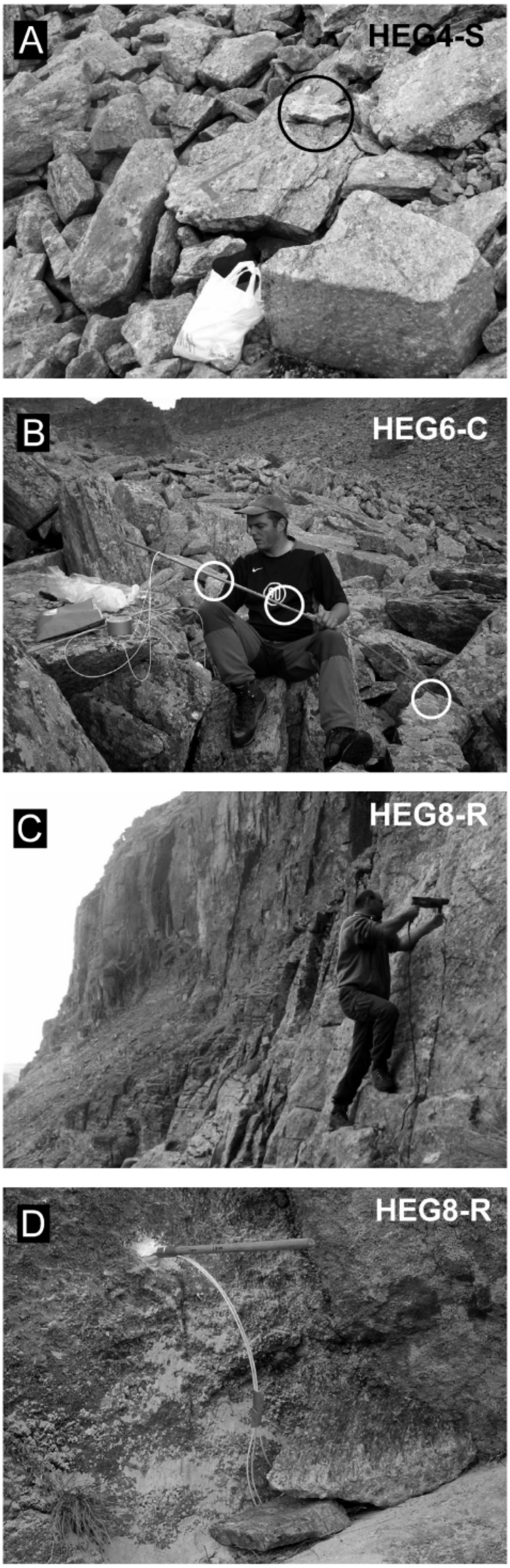


Figure 2: Visual examples of location and instrumentation of different temperature sensor locations in the study area. A): site HEG4-S where only GST is measured after instrumentation. The sensor is sheltered from direct solar radiation by a thin platy rock indicated by the black circle. B): site HEG-C during instrumentation with three temperature sensors taped to a wooden stick and later placed into the voids of the coarse sediments. White circles indicate the three sensors: C): and D): site HEG8-R during and after completion of the measurement site.

sensors in the MTDs have an accuracy of +/-0.05°C (range: -40 to +100°C, calibration drift of <0.01°C a^{-1}). Temperature was logged continuously every 60 minutes at all sites.

At further four sites (HEG5-F, HEG6-C, HEG7-R, and HEG8-R) vertical temperature profiles down to depths of 30 to 175 cm were monitored. At these four sites, 3-channel dataloggers with three temperature sensors each have been used (GeoPrecision, Model M-Log6). Each of the three sensors is connected to the MTD by a teflon cable. At site HEG5-F temperature in fine-grained material were measured. Sensors were installed at depths of 3, 10 and 40 cm. The cables connecting the sensors with the logger were affixed to a wooden stick by a protecting tape. Sieving analyses of a soil sample (ca. 1 kg) from site HEG5-F determining the grain size distribution of the sand fraction and smaller was carried out. In doing so, the requirements of ÖNORM 4412 using conventional wet sieving and half to full grade (psi units) intervals in mesh size between sieves were considered (Evans and Benn, 2004). The results showed that material is moderately sorted sand (91.6%) with a minor content of silt and clay (8.4%).

At site HEG6-C temperatures in the block voids of coarse-grained sediments were measured. The three sensors with the connecting teflon cables were attached to a wooden stick with a tape and placed into the voids of the coarse sediments of the intact rock glacier at depths of 50, 100 and 175 cm. At sites HEG7-R and HEG8-R bedrock temperature was measured. Boreholes (16 mm wide) were drilled at each site 30 cm horizontally into the bedrock. To measure near rock surface temperature, sensors were installed at 3, 10 and 30 cm using a stick and a tape as described above. After sensors installation, the borehole was refilled with fine quartzite sand and sealed with silica gel to avoid air circulation in the borehole.

The analyses of the ground temperature data covered the values for mean annual ground temperature (MAGT) at different depths, mean annual ground surface temperature (MAGST), and the elevation of the zero-degree isotherm (ZDI). The ZDI might be regarded as a proxy for permafrost occurrence. However, the ground surface temperature and hence the ZDI is not a measure of permafrost in a strict sense. The temperature at the top of permafrost (TTOP) is a result of the combination of air temperature, solar radiation, surface offset (snow, vegetation, ground surface characteristics) and thermal offset (related to active layer characteristics such as thickness, porosity moisture).The TTOP is generally cooler compared to the mean surface temperature (Smith and Riseborough, 2002). The ZDI was calculated for each sensor using a vertical temperature gradient of 6.34 K km^{-1} (as in the permafrost distribution model). The time frame for the analyses was in general the hydrological year (1 October to 30 September). The mean values were calculated on the basis of two to five years of measurement data.

4. Results

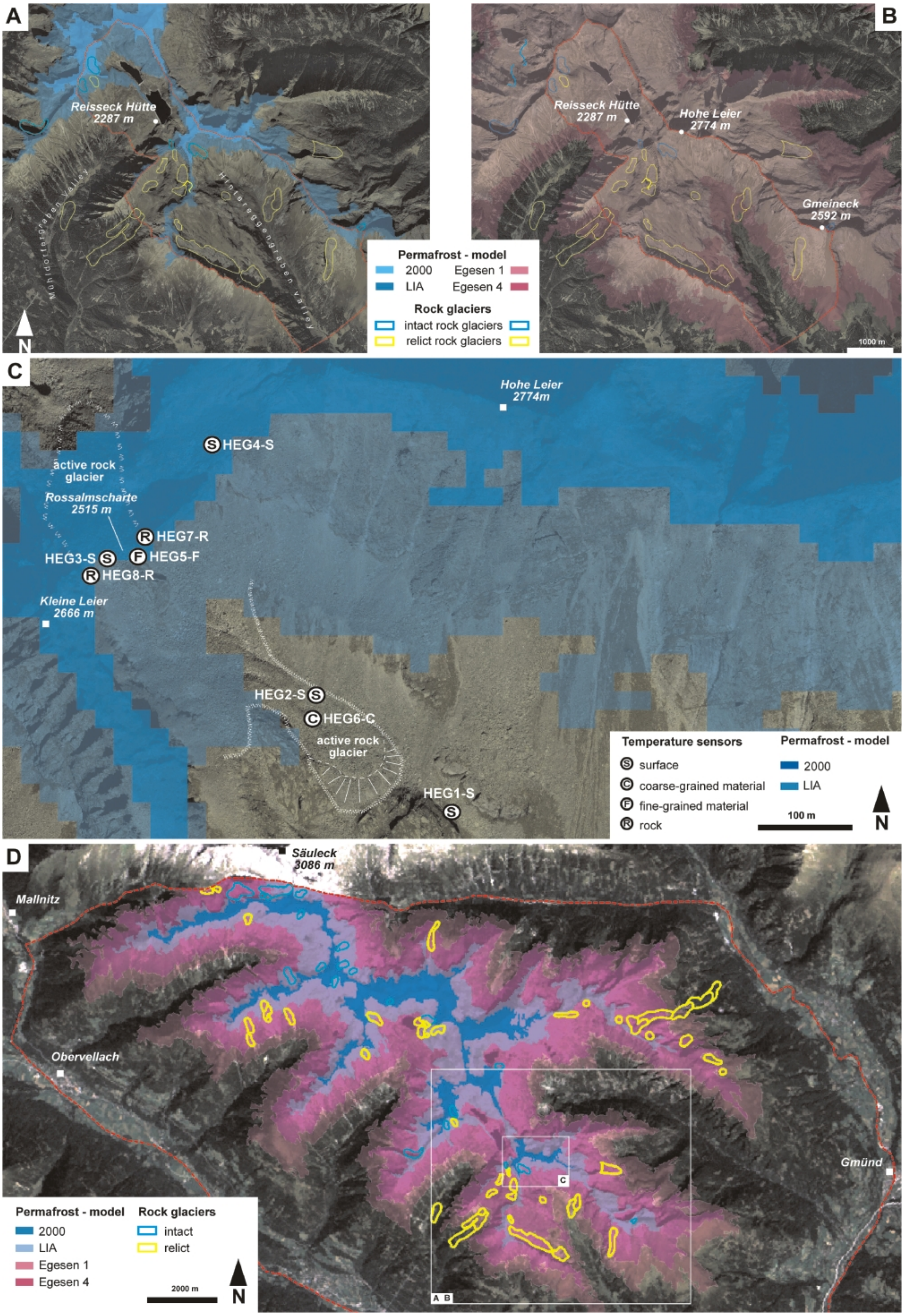
4.1 Potential permafrost distribution modelling and rock glacier distributions

The Reisseck Mountains house 49 rock glaciers, thereof 18 intact (two polymorph rock glaciers sensu Frauenfelder and Kääb, 2000) and 31 relict rock glaciers (six of the rock glaciers are polymorph). In the study area HEG four intact and 13 (including one polymorph) relict rock glaciers were detected (Fig. 3). The medians of the lowest point of intact and relict rock glaciers are, respectively, at elevations of 2450 m and 2160 m a.s.l. Table 3 gives an overview of topographical parameters of the rock glaciers in the Reisseck Mountains.

The overall spatial coverage of potential permafrost areas

Site	Sensor depths [cm]	Data series	Aspect [-]	Slope [-]	Elevation [m a.s.l.]	Comments
HEG1-S	0	30.09.06–17.10.11 (ca. 5 years)	SE	25	2320	1-channel MTD; lowest site; coarse-grained blocks
HEG2-S	0	30.09.06–17.10.11 (ca. 5 years)	S	20	2404	1-channel MTD; located at the surface of an intact rock glacier consisting of coarse-grained blocks
HEG3-S	0	30.09.06–06.11.08 (ca. 2 years)	S	25	2501	1-channel MTD, located at coarse-grained blocks
HEG4-S	0	30.09.06–17.10.11 (ca. 5 years)	W	30	2600	1-channel MTD, located at coarse-grained blocks
HEG5-F	3, 10, 40	30.09.06–05.11.08 (ca. 2 years with data gaps)	S	5	2500	3-channel MTD, in fine-grained sediments; located near site HEG3-S
HEG6-C	50, 100, 175	30.09.06–15.09.08 (ca. 2 years with a data gaps)	SE	20	2401	3-channel MTD; in coarse-grained sediments at the rock glacier surface; located near site HEG2-S
HEG7-R	3, 10, 30	30.09.06–12.08.09 (ca. 3 years)	W	85	2510	3-channel MTD; W-exposed rock wall site
HEG8-R	3, 10, 30	30.09.06–03.02.09 (ca. 2.5 years)	E	75	2515	3-channel MTD; E-exposed rock wall site

Table 2: Sites where ground surface and near surface temperature has been monitored at the study area Hintereggen Valley-Hohe Leier (HEG) by using miniature temperature dataloggers (MTD). The first four sensors measure ground surface temperature, the second four sensors temperature at different depths. Abbreviations: S=ground surface, F=fine-grained material, C=coarse-grained/blocky material, r=rock wall. Locations of the eight MTD sites are indicated in Fig.1 and Fig.3C.


A
Reisseck Hütte
2287 m
Mühldorfergraben Valley
Hintereggengraben Valley
N
B
Reisseck Hütte
2287 m
Hohe Leier
2774 m
Gmeineck
2592 m
1000 m
Permafrost - model
2000
LIA
Egesen 1
Egesen 4
Rock glaciers
intact rock glaciers
relict rock glaciers
C
Hohe Leier
2774m
HEG4-S
active rock glacier
Rossalmscharte
2515 m
HEG7-R
HEG3-S
HEG5-F
HEG8-R
Kleine Leier
2666 m
HEG2-S
HEG6-C
active rock glacier
HEG1-S
Temperature sensors
surface
coarse-grained material
fine-grained material
rock
Permafrost - model
2000
LIA
100 m
N
D
Säuleck
3086 m
Mallnitz
Obervellach
Gmünd
C
A B
Permafrost - model
2000
LIA
Egesen 1
Egesen 4
Rock glaciers
intact
relict
2000 m
N

Activity	n	LL	UL	ML	MW	HPC
relict	31	2160	2310	320	225	2580
intact	18	2450	2610	290	205	2802
sum	49	2303	2420	320	223	2662

Table 3: Topographical parameters (median) of rock glaciers in respect to their activity status in the Reisseck Mountains. Abbrevations: n=number, LL=lower limit, UL=upper limit, ML=length, MW=width, HPC=highest point in catchment area.

for the entire Reisseck Mountains ranges from 2.5 % in *Sc-2000* to 42.5 % in scenario *Sc-E4* (for details see Tab.4). Figure 4 shows the percentage of the potential distribution of discontinuous permafrost of the different scenarios in elevation belts of 50 m in the study region Reisseck Mountains and the study area HEG. Recent permafrost occurrence in the Reisseck Mountains as represented by the location of intact rock glaciers compared to the simulation of Sc-2000 shows that all rooting zones and 28% of frontal zones are within potential permafrost areas (Table 4, cf. Fig. 4 for HEG). The coverage of occurrence of discontinuous permafrost within altitudinal belts gives significant larger values beginning with 2700 m a.s.l. (87%, Fig. 4).

In contrast to other articles, where the lower limit of potential permafrost occurrence was approximated by the lower limit of active/inactive rock glaciers (*cf.* Lambiel and Reynard, 2001), we determined the lower limit of discontinuous permafrost for the *Sc-LIA* by a temperature depression of Δt = -1.4 K (Böhm 2006). In terms of interpretation we have to take into account that according to the slow reaction of permafrost to changing climatic conditions (Haeberli et al., 1993), some rock glaciers were probably already inactive during that time.

Modelling results for Sc-LIA in the Reisseck Mountains show a strong increase of potential permafrost areas beginning in the 2550 – 2600 m a.s.l. belt with 60% to a spatial coverage of 93 % above 2650 m a.s.l compared to 13 % in Sc-2000. This observation is crucial in respect to the location of intact rock glaciers (Fig. 4). 83% of the frontal zones and 100 % of the rooting zones of the intact as well as already 10% of the frontal zones and 45% of the rooting zone of the relict rock glaciers are within the potential permafrost areas *(Sc-LIA*, Table 5). For modelling potential permafrost distribution during the Younger Dryas period, we assumed four temperature depressions of Δt = -2.5 (*Sc-E1*) to Δt = 4.0 K (*Sc-E4*) relative to *Sc-LIA* in order to determine simulations of the potential distribution of discontinuous permafrost during the Younger Dryas.

The positions of relict rock glaciers relative to the lower limit of potential discontinuous permafrost are crucial in terms of the validation of the model, despite the fact that rock glaciers have a different microclimate compared to its surrounding due to the commonly coarse-blocky surface. As we assume that the relict rock glaciers were formed after the Egesen maximum, by definition at least the rooting zones of the relict rock glaciers must be inside the potential permafrost areas. Results show that in all scenarios more than 85% of frontal zones and nearly all rooting zones (97%) (Table 5) are within the modelled potential permafrost areas (Fig. 3A, B, D). Even the highest points of the lowest units of five out of six multi-unit rock glaciers are situated in potential permafrost areas (*Sc-E1-E4*, Table 5, Fig. 3A, B, D).

The potential distribution of discontinuous permafrost in the local scale of the study site HEG gives interesting results with respect to the location of temperature sensors. The scenario *Sc-2000*, which displays the recent situation, shows sparse occurrence of permafrost such as the E-face of the mountain Kleine Leier above the rooting zone of the active rock glacier Rossalmscharte. Furthermore, the uppermost part of the cirque north of the saddle Rossalmscharte (Fig.3C) is modelled as potential permafrost areas which coincide well with the small active rock glacier situated just beneath the saddle Rossalmscharte. Only temperature sensors HEG-4S and HEG-7R are under permafrost conditions in the *Sc-2000* (Fig. 1, Fig. 3C). However, results from *Sc-LIA* show most sites – apart from HEG-1S and HEG-2S and HEG6-C – are within potential permafrost occurrence (Fig. 3C).

4.2. Ground thermal regime of the study area HEG

Results from the ground temperature monitoring are shown in Figure 5 showing that the MAGT and the MAGST are positive at seven out of eight MTD sites. Only at the monitoring site with the coarse-grained blocky material (HEG6-C), the MAGT is slightly negative ranging from -0.2 at a depth of 50 cm to about -1.0°C at 175 cm. However, during the period 2006 - 2011 the inter-annual difference at all eight MTD sites

Figure 3: Results of modelling potential permafrost distribution. A): Study area Hintereggengraben Valley-Hohe Leier (HEG) with results from the scenarios *Sc-2000* and *Sc-LIA* and rock glacier distribution. B): Study area HEG with results from the four Egesen scenarios *Sc-E1* to *Sc-E4* and rock glacier distribution. C): Valley head of HEG with results from *Sc-2000* and *Sc-LIA* and MTD sensor locations (see Table 2). D): Entire study region Reisseck Mountains with results from the scenarios *Sc-2000*, *Sc-LIA*, and *Sc-E1* and *Sc-E4* as well as rock glacier distribution.

Area of permafrost	Sc-2000	Sc-LIA	Sc-E1	Sc-E2	Sc-E3	Sc-E4
Overall area [km²]	320					
	Potential discontinuous permafrost					
Absolute [km²]	9.94	35.73	96.70	109.37	122.22	134.57
Percentage [%]	3.1	11.1	30.2	34.2	38.2	42.1
	Potential sporadic permafrost					
Absolute [km²]	1,48	2,37	-	-	-	-
Percentage [%]	0.5	0.8	-	-	-	-

Table 4: Spatial distribution of potential discontinuous permafrost (absolute und percentage) of all scenarios and sporadic permafrost of selected scenarios.

Activity status	relict (n = 31)				intact (n = 18)			
Rock glacier zone	frontal zone		rooting zone		frontal zone		rooting zone	
Number/percent	n	%	n	%	n	%	n	%
Sc-2000	0	0	2	6	5	28	18	100
Sc-LIA	3	10	14	45	15	83	18	100
Sc-E1	27	87	30	97	18	100	18	100
Sc-E2	27	87	30	97	18	100	18	100
Sc-E3	28	90	30	97	18	100	18	100
Sc-E4	30	97	31	100	18	100	18	100

Table 5: Potential permafrost distribution in the frontal and rooting (i.e. upper end) zones of intact and relict rock glaciers in respect to model results for *Sc-2000*, *Sc-LIA*, and *Sc-E1* to *Sc-E4* in the entire Reisseck Mountains.

was up to 2°C caused by the exceptional warm winter 2006/07 and the rather cool winter 2007/08. Hence, if looking only at single years, also the two sites HEG1-S and HEG2-S (surface sites) are close (+0.5°C) or below 0°C.

Figure 6 shows the subsurface isotherms at the four MTD sites where temperature is monitored continuously at three different depths. This graph shows mean monthly temperature values of between +11.4 and -7.4°C. At the fine-grained site (HEG5-F) the penetration of the warming and cooling signal into the ground seems to be less efficient compared to the rock wall sites. At least for the cooling signal, the same is true if the values from HEG5-F are compared with the values from the coarse-grained site (HEG6-C). Generally HEG5-F is cha-racterised by moderate cool as well as warm temperatures. At the two rock wall sites HEG7-R and HEG8-R warming and cooling is quite comparable to each other. The latter is the warmer rock wall site. In contrast, at the coarse-grained site HEG6-C cooling is very effective all the way down to -175 cm, whereas warming during summer is substantially slower. This observation is relevant for the general ground cooling in the study region due to the widespread occurrence of coarse-grained sediments partly forming rock glaciers.

Calculating the zero-degree isotherm (ZDI) is an appropriate approach in order to directly compare the mean ground temperatures between all sites. According to the applied lapse rate, the site with the lowest calculated ZDI is the coarse-grained site

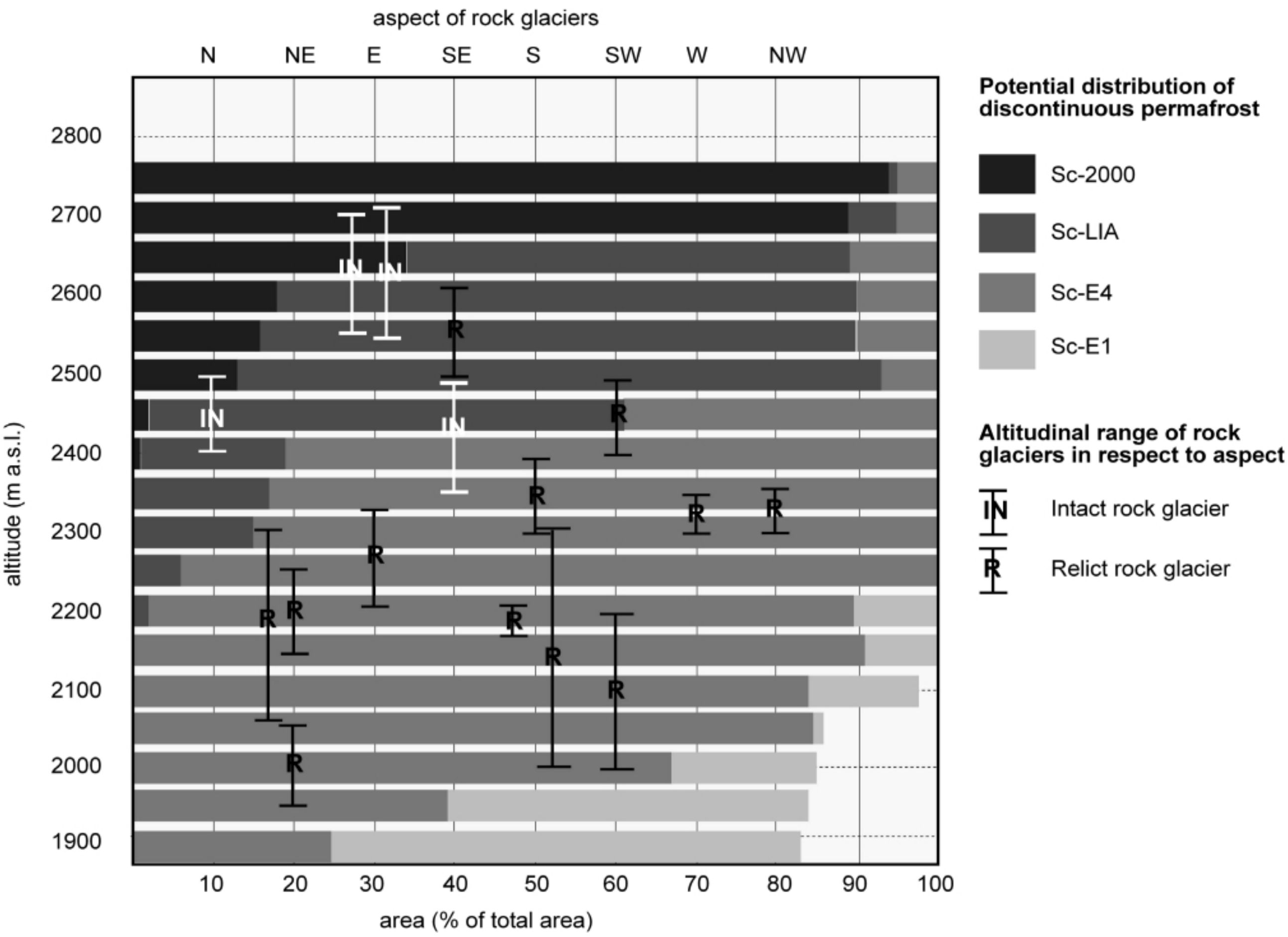


Figure 4: Results of four scenarios of modelling potential permafrost distribution in the study area HEG with respect to altitudinal belts (of 50 m steps) as well as altitudinal range of rock glacier range with respect to their activity status.

HEG6-C with 2370 m a.s.l. with a range of 2500 (in 2006 - 2007) to 2240 (in 2007 - 2008) m a.s.l. The second lowest ZDI was calculated for the neighbouring site HEG2-S with almost 2500 m a.s.l. as a mean value, closely followed (+50m) by site HEG1-S. Interestingly, the four sites HEG3-S, HEG4-S, HEG5-F and HEG7-R show very similar values of ZDI with 2760 to 2795 m.a.s.l. despite substantial differences in the local topographical settings.

5. Discussion

We used a simple model to determine potential distribution of discontinuous permafrost during different time periods in the Lateglacial and Holocene periods. Despite this simplicity, modelling results of the potential distribution of discontinuous permafrost show satisfying results in the scenarios of *Sc-2000* and *Sc-LIA* compared to the location of rock glaciers in the study area as well as the comparison with recent temperature data. Scenarios of the *Sc-2000* and *Sc-LIA* coincide well with the location of frontal and rooting zones of intact rock glaciers. From *Sc-LIA* to *Sc-2000* the area underlain by permafrost decreases remarkably (Fig. 3 and 4, cf. Lambiel and Reynard, 2001) but rooting zones are currently still located in potential areas of discontinuous permafrost. Consequently, the occurred temperature increase of *Δt* = +1.4 K since LIA (Böhm 2006) is - as expected - very unfavourable for the thermal conditions of intact rock glaciers, especially in this area of marginal permafrost occurrence of the Reisseck Mountains. Due to simulated depression of lower limit of permafrost of 160 m from *Sc-2000* to *Sc-LIA*, we can assume that most of the now inactive rock glaciers were active during the LIA (Haeberli et al., 1993).

Modelling the permafrost occurrence in the Younger Dryas was conducted with four different temperature depressions *(Sc-E1* to *Sc-E4*). Apart from a few very low located relict rock glaciers, we conclude that a temperature depression of *Δt* = -3.0 K (represented by *Sc-E2*) calculated from LIA as sufficient to generate permafrost favourable conditions in all rooting zones of the nowadays relict rock glaciers in the Reisseck Mountains. However, these comparably low located fea-

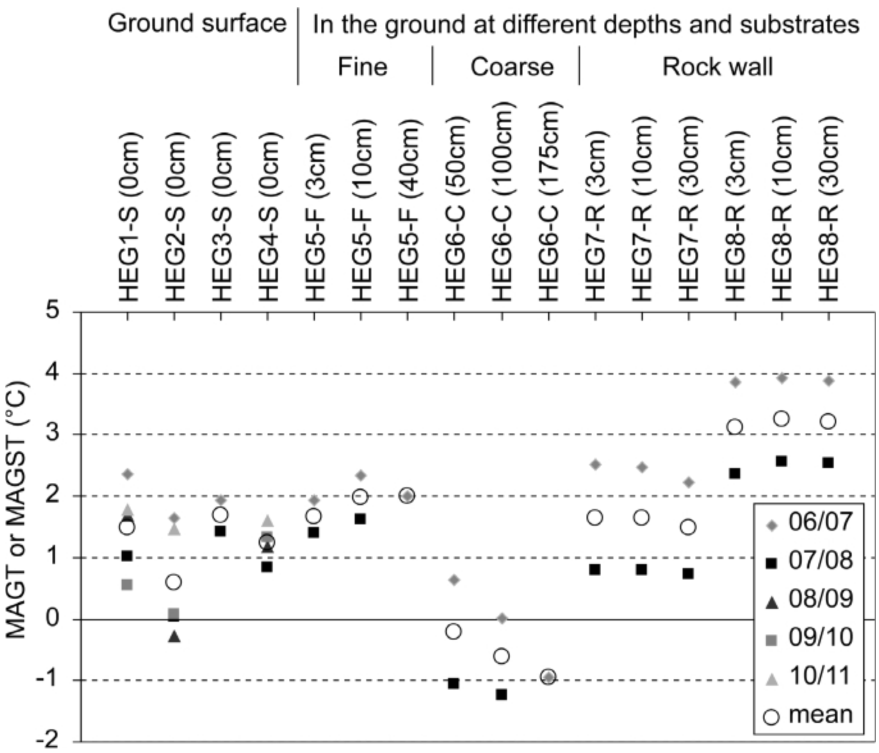


Figure 5: Mean annual ground temperature (MAGT) or mean annual ground surface temperature (MAGST) at all MTD sites for the measurement years 2006 to 2011. See Table 2 for details on MTD sites and Table 6 for results. For locations refer to Fig. 1 and Fig. 3C.

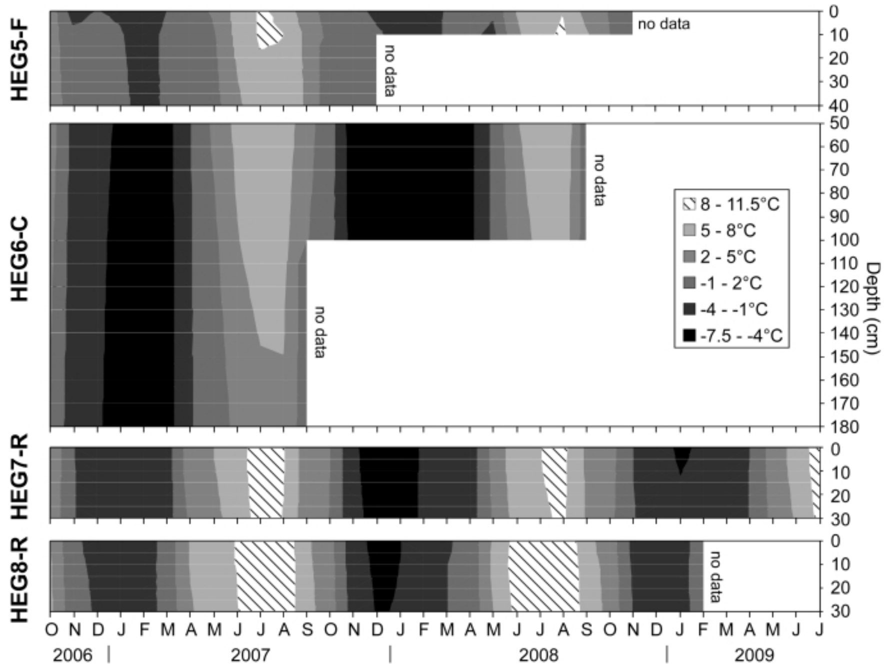


Figure 6: Subsurface isotherms at the four MTD sites with temperature profile measurements (data at three different depths each) for the period October 2006 up to July 2009 based on monthly mean values with linearly interpolated values between sensor depths and extrapolated to the surface at HEG5-F, HEG7-R and HEG8-R. For sensor depths see Table 1, for locations refer to Fig. 1 and 3C.

tures are possibly of pre-Younger Dryas age but still younger than the Gschnitz stadial (>15.4 ka BP; Kerschner and Ivy-Ochs, 2007) due to the substantially larger glacier extent during the Gschnitz stadial (Schuster et al., 2006). Kerschner and Ivy-Ochs (2007) suggest summer temperature depression of a -3.5 K for interior Alpine valleys (and -20% precipitation in relation to today) for an early Younger Dryas scenario. Our corresponding model output of Sc-E3 (Δt = -3.5 K) reveals that all root zones and -except of three - all relict rock glaciers are located entirely within potential permafrost areas. Therefore all of these rock glaciers seem to be younger than Egesen I stage in the Younger Dryas.

The depression values of the lower limits of permafrost (*Sc-2000* compared to *Sc-E1* to *ScE4*) were calculated with -560 m (*Sc-E1*) to -780 m (*Sc-E4*). Kerschner et al. (2008) state a depression from at least 500 to 600 m during the later phase of the Egesen compared to the lower limit of permafrost at present. This depression value was presumably higher during Egesen maximum (Egesen I), where rock glaciers were presumably able to form in the many of glacier-free cirqus of the study region Reisseck Mountains. Furthermore, it is getting evident that a change in the temperature lapse rate during the Egesen compared to today has a major influence on the lower limit of permafrost based on a given temperature depression. Due to the lack in knowledge about lapse rates during the Lateglacial period, a best-guessed local lapse rate with present data (for the more recent past) or common regional lapse rates must be used.

Our scenario *Sc-E2* (Δt = -3.0 K) simulates a median of the lower limit of potential discontinuous permafrost of 1940 m a.s.l., resulting in a depression of 630 m compared to *Sc-2000* which is more than the depression of the glacier equilibrium lines of app. 200 m for the Central Alps (Kerschner and Ivy-Ochs, 2008). Frauenfelder et al. (2001) show that for a comparable temperature depression in the Younger Dryas of Δt = -3.0 K the depression of the lower limit of permafrost in the Central Engadin Mountains (Switzerland) would presumably be around 500 – 600 m. This suggests a strongly reduced precipitation and a larger abundance of high mountain permafrost in the Younger Dryas which was already shown e.g. by Haeberli (1982).

At the local scale of the study site HEG the potential distribution of discontinuous permafrost in *Sc-2000* is supported by ground temperature data. Nearly all monitoring sites showed positive MAGT and/or MAGST at different depths. This might be regarded as indicators for non-permafrost areas. However, an open question is the thermal offset between the MAGST and the TTOP as well as the thermal inertia ice-rich debris, which need long time to melt due to latent heat exchanges. In general, the MAGST is higher compared to TTOP (Smith and Riseborough, 2002) meaning that permafrost might exist below the active layer even at positive temperatures at the surface, related to reasons mentioned already above. A clear decrease in the mean value away from the ground surface is shown for site HEG6-C with a decrease in the mean temperature by almost 1°C at a vertical distance of only 1.25 m. However, the depth of the active layer is thicker than the measurement profiles at all MTD sites therefore neither the active layer thickness, nor (permafrost) temperatures at greater depths are known. Furthermore, as shown by our data, many of the MTD sites with positive MAGST or MAGT have at least values of between 0°C and 1°Cvery close to 0°C if looking on single years. These results might be seen as further indicators that the lower limit of present permafrost is at elevations close to the MTD sites. In terms of validation, the MTD sites are in close vicinity to simulated permafrost areas in *Sc-2000* and can therefore be addressed as located in the thermal transition zone. However, long-term ground temperature monitoring is essential to better understand current and hence past but also future ground thermal and permafrost conditions. Even more, a borehole with temperature measurements down to depth exceeding 5 or even 10 m would be very helpful better understanding the ground thermal conditions at the study site and consequently the potential rock glacier favourable periods in the past.

For future perspectives of a proceeding permafrost degradation and hence predicted disappearance in the European Alps, the thermal lapse rate thresholds for the existence of permafrost can be calculated (basis: t_0 = 2000, lapse rate: 6.34 K km^{-1}): Δt = + 2.95 K for the study region Reisseck-Mountains (highest point: Großes Reisseck, 2965 m a.s.l.) and Δt = +1.74 K for the study area HEG (highest point: Hohe Leier, 2774 m a.s.l.). These temperature scenarios are likely to happen until the following years according to the IPCC "business as usual" scenario IS92a (IPCC, 2001): c. around 2080 for the study area HEG and not before 2100 for the Reisseck Mountains. The model does not exceed the year 2100.

6. Conclusions

The presented approach based on terrain parameters validated with field data gives interesting results in simulating present and reconstructing past distribution of discontinuous permafrost in the Little Ice Age as well as in the Younger Dryas of the Alpine Lateglacial. A depression of ca. 560 m in the lower limit of permafrost and a temperature depression of about Δt = -2.5 K (to LIA) is likely as a scenario for thermal conditions during parts of the Younger Dryas. However, one major uncertainty is the mean temperature lapse rate which was valid for the climatic conditions during the Younger Dryas.

One major uncertainty is the mean temperature lapse rate which was valid for the climatic conditions during the Younger Dryas. Furthermore, ground temperature monitoring is currently carried out at the surface and at depths down to 1.75 m thereby not reaching the permafrost table. Therefore, a deeper borehole would be desirable in the study area to better understand present and better interpret possible past permafrost conditions.

Further analyses regarding a closer look of potential distribution of permafrost during younger stadials e.g. Kartell and Kromer seem to be necessary to better understand the formation of the rock glaciers in this particular part of the Austrian Alps. Additionally due to the lack of information about dating of rock glacier age in the study region (apart from relative dating of three rock glaciers in the Dösen Valley; Kellerer-Pirklbauer, 2008), relative and absolute dating of rock glacier surfaces would be an important step forward to get information about the temporal origin of this permafrost landforms and its characteristics in the past. Consequently this would improve the model to reconstruct palaeo-climatic conditions.

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