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# Ground surface temperature and permafrost evolution in the Hohe Tauern National Park, Austria, between 2006 and 2012: Signals of a warming climate?

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## Abstract

Permafrost is an important element of high mountain environments and is very sensitive to ongoing present climate warming. Consequently, knowledge about permafrost and its changes are of increasing relevance for the public. Longer time series are necessary to characterise the average ground thermal regime relevant for understanding permafrost distribution and changes. Long-term monitoring of ground temperature is therefore essential. However, so far such data are widely lacking in Austria. Within the project ALPCHANGE, a long-term monitoring program was initiated in 2006 at a number of study areas in the Hohe and Niedere Tauern Ranges in the Central Alps. In this study up to six years of data from five different study areas in the Hohe Tauern National Park with altogether 36 continuous ground temperature measurement sites are presented and discussed. Results clearly show high interannual variations. However, at most sites a trend towards warmer temperature can be observed. This evolution is despite the fact that the sites have big differences in the duration of the winter snow cover strongly influencing the ground thermal regime. Interestingly, the warming trend is very clear and distinct in the western part of the national park (area around Großglocker-Pasterze-Schober Mountains) but substantially weaker in the eastern part (Ankogel Mountains). Permafrost at north-facing slopes can be expected as low as 2500 m a.s.l. whereas on south-facing slopes permafrost is most likely absent below 2820 m a.s.l. Expected warmer ground temperatures during the winter half-year imply for instance rock fall events in periods which are currently thought to be safe for mountaineers and animals in the Hohe Tauern National Park.

## Keywords

permafrost, ground temperature change, Tauern Range, Hohe Tauern National Park, global warming, climate change

## Introduction

Permafrost in warm climates such as the European Alps is particularly sensitive to the ongoing present climate warming. Permafrost degradation has also a significant impact on people as well as alpine and low-elevated infrastructure considering for instance destabilizing mountain slopes as natural hazards (e.g. HUGGEL et al. 2010, KELLERER-PIRKLBAUER et al. 2012, KERN et al. 2012). Consequently, permafrost existences and its changes are of increasing relevance for the Austrian public. The Hohe Tauern Range with its c.1900 km² large Hohe Tauern National Park houses the highest summit of Austria (Großglockner, 3798 m a.s.l.) and large permafrost areas. Therefore, this national park is of particular interest and significance for permafrost research in Austria.

Permafrost is defined as ground – soil or rock with ice of different origin and organic material – that remains at or below 0°C for at least two consecutive years. Permafrost in mountain areas in mid- and low-latitudes is generally relatively warm with only some degrees below 0°C. Its distribution is closely related to terrain parameters such as elevation, slope orientation, slope gradient, ground material and snow cover characteristics. The top layer of permafrost is seasonally influenced by thawing (summer) and freezing (winter). This layer is termed "active layer". Its thickness might vary from between some decimetres to meters depending to the ground and topoclimatic conditions of a given site (FRENCH 2007).

Permafrost is much more difficult to delineate compared to for instance glaciers due to its definition by temperature. However, knowledge about permafrost distribution is steadily increasing based on inventories of permafrost evidences (e.g. CREMONESE et al. 2011) or based on permafrost modelling approaches (RISEBOROUGH et al. 2008) at national (EBOHON & SCHROTT 2008), mountain range (BOECKLI et al 2012) or even global scale (GRUBER 2012). Feeding such models depends on field data coming from different sites of the chosen modelling domain (e.g. the Alps). However, the quality of the modelling results also depends on number, quality, type and spatial distribution of the field data. Furthermore one has to keep in mind that variations of the mean annual ground surface temperature (MAGST) within short distances might be some degrees Centigrade even in homogeneous terrain (GUBLER et al. 2011). This further highlights the difficulties in modelling the "real" permafrost distribution and the strong need for good field data.

Furthermore, longer time series covering time-spans exceeding more than one year are needed in order to characterise the average ground thermal regime relevant for permafrost distribution because of thermal inertia of permafrost. Long-term monitoring of ground temperature is therefore essential for permafrost understanding. However, so far such data are widely lacking in Austria. Within the project ALPCHANGE, a long-term monitoring program was initiated in 2006 at a number of study areas in the Hohe and Niedere Tauern Ranges in the Central Alps. The monitoring project was continued within the two projects PermaNET and permAfrost. Five of the study areas are located in the Hohe Tauern National Park. Results from these sites are presented and discussed here. Therefore this paper aims to increase the understanding of the thermal conditions – particularly permafrost – in the Hohe Tauern National Park.

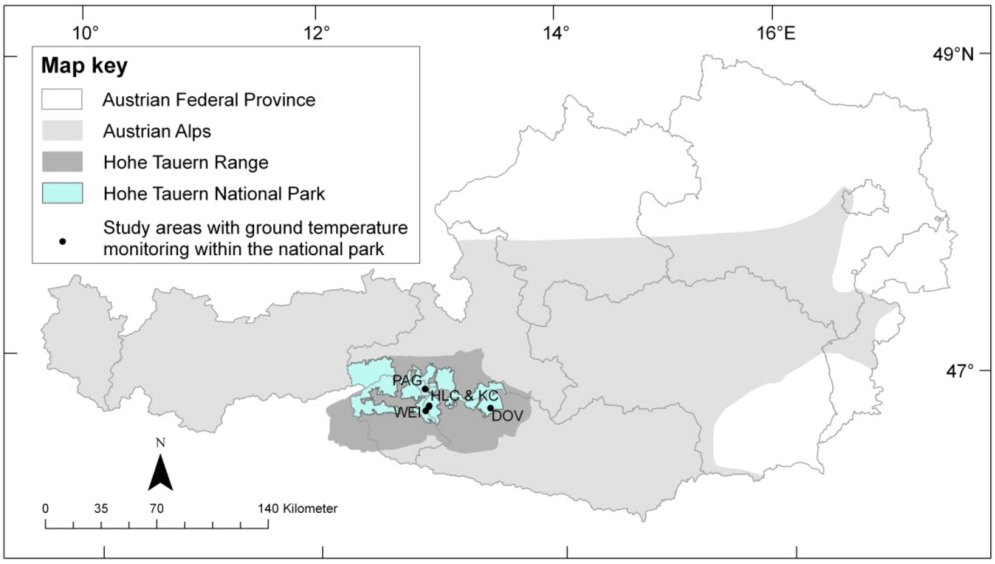


Figure 1: Location of the five study areas within the National Park Hohe Tauern where ground temperature monitoring is carried out since 2006. Abbreviations of the study areas: KC=Kögele Cirque, HLC=Hinteres Langtal Cirque, WEI=Weissen Cirque, PAG=Pasterze-Großglockner area, DOV=Dösen Valley. For available data for each site see Table 1.

## Study area

The five study areas relevant here are all located within the area of the Hohe Tauern National Park (Fig. 1). Three study areas are situated in the Central Schober Mountains (Kögele Cirque, Hinteres Langtal Cirque, Weissen Cirque/WEI), one in the Glockner Mountains (Pasterze-Großglockner area) and one in the Ankogel Mountains (Dösener Valley/DOV). Fig. 2 depicts in more detail the topographical situation of the five sites including the locations of the ground temperature sensors relevant for this study.

Kögele Cirque (KC) and Hinteres Langtal Cirque (HLC)

The two neighbouring cirques KC and HLC are located at N46°59´ and E12°47´. The first cirque houses an active rock glacier, the second a debris-covered glacier remnant (KELLERER-PIRKLBAUER & KAUFMANN 2007). The cirques are orientated towards northwest with high crests and mountain tops slightly exceeding the 3000-m level to the south and east. KC comprises 0.31km² and is delineated at its lower end by a distinct Little Ice Age (LIA) latero-terminal moraine. The altitude range of the entire cirque is ca. 2600-3030 m a.s.l. (Fig. 2)

HLC is morphologically dominated by the tongue-shaped Hinteres Langtalkar Rock Glacier. The rock glacier is 900 m long, up to 300 m wide, covers an area of 0.17 km², consists of mica-schist and amphibolites and ranges from 2455 to 2720 m a.s.l.. Its dimensions make this rock glacier one of the larger rock glaciers of the Central Alps. The front of this rock glacier advanced 80 m (horizontal component) from 1991-1998 (KAUFMANN & LADSTÄDTER 2010). The annual rock glacier movement variation is in accordance to other monitored rock glaciers in the region or in the entire European Alps (DELALOYE et al. 2008) due to the strong relationship between rock glacier velocity and climate (KELLERER-PIRKLBAUER & KAUFMANN 2012).

The mean annual temperature in 2500 m a.s.l. in the Central Schober Mountains – and therefore at KC, HLC and the Weissen Cirque (WEI) – increased from -2.08 in 1961-1983 to -1.35 in 1984-2006 with a significant rise in the mean annual temperature by 1.31 since 1961 (TAUCHER et al. 2009, TAUCHER 2010). According to the same authors, mean annual precipitation was about 2000 mm in 2500 m a.s.l. during the period 1961-2006 without a statistical significant trend.

Weissen Cirque (WEI)

WEI is a west-facing cirque housing a slowly moving tongue-shaped rock glacier located at N46°57´ and E12°45´ and between 2615 and 2790 m a.s.l. This rock glacier consists of an active upper lobe presumably overriding an inactive lower lobe, hence can be regarded as a polymorphic rock glacier. The rock glacier has a length of 500 m, a maximum width of 300 m, and a surface area of 0.11 km². Different types of mica schist build up the rock glacier. Present mean surface velocities are below 10 cm $a^{-1}$ (KAUFMANN et al. 2006, KELLERER-PIRKLBAUER & KAUFMANN 2012)

Dösen Valley (DOV)

The study area DOV is a glacially shaped, W-E trending valley in the Ankogel Mountains at N46°59´ and E13°17´ between 2355 and 2650 m a.s.l.. The upper-most part of the valley is characterised by four north-to-west facing rock glaciers, a cirque floor with a tarn lake and distinct terminal moraines of Younger Dryas age. The rock glaciers in DOV consist primarily of granitic gneiss. The largest rock glacier is an active monomorphic tongue-shaped rock glacier with a length of 950 m, a width of maximum 300 m and a surface area of 0.19 km². Mean surface velocities during the last decades were below 40 cm a-1 (KAUFMANN & LADSTÄDTER 2007, KELLERER-PIRKLBAUER & KAUFMANN 2012).

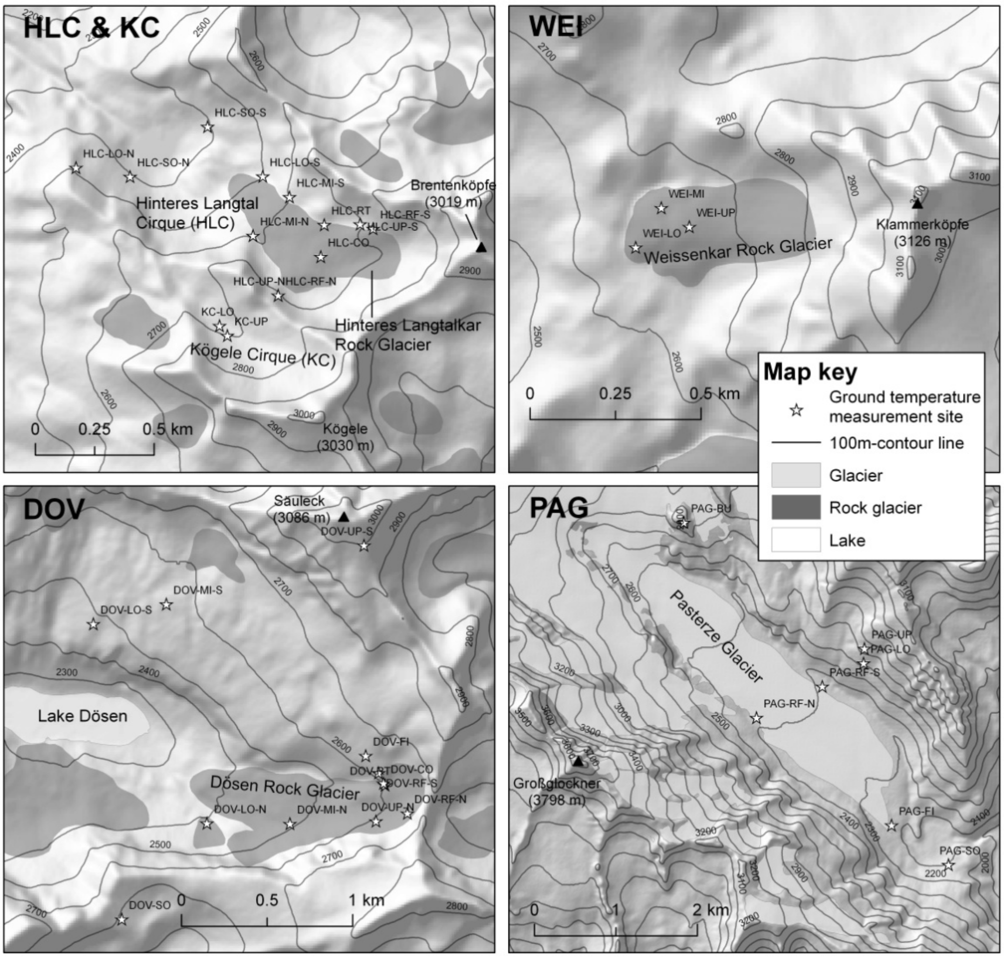


Figure 2: Detailed maps of the five study areas with the locations of all miniature temperature dataloggers (MTD). For details and description of the MTD sites and data series see Table 1. Glaciers are only partly shown in PAG.

Pasterze-Großglockner area (PAG)

The Pasterze Glacier (47˚05'N, 12˚44'E) is situated at the foot of the Großglockner mountain (3798 m a.s.l.) which is highest summit of Austria. Pasterze Glacier is a compound valley glacier fed by a number of tributaries. The glacier reaches a length of 8.4 km, ranges from ca. 2065-3500 m a.s.l. and covers an area of 17.5 km² (in 2002). The glacier is the largest ice mass in Austria and an important site for the tourist industry (famous look-out point Franz-Josefs-Höhe) and hydropower production. For details on the glacier and the surrounding see e.g. KELLERER-PIRKLBAUER (2008), KELLERER-PIRKLBAUER et al. (2008, 2012) or KERN et al. (2012).

## Material and Methods

At each study area several miniature temperature dataloggers (MTD) were placed in 2006 at different elevations, aspects, substrates and depths in the ground automatically logging ground temperatures at 1h-intervall. Instrumentation was financed by the nationally-funded (FWF/Austrian Science Fund) *ALPCHANGE* project. Following maintenance was financed by the EU-project *PermaNET* (until 2010) and the nationally-funded (ÖAW/Austrian Academy of Science) *permAfrost* project. The used MTDs are either 1-channel dataloggers (GeoPrecision, Model M-Log1) monitoring with one temperature sensor or 3-channel dataloggers (GeoPrecision, Model M-Log6) monitoring with three sensors at different depths (Table 1). According to the producer, the used PT1000 temperature sensors have an accuracy of ±0.05°C, a range -40 to +100°C and a calibration drift <0.01°C a$^{-1}$.

Table 1: The 36 sites in the Hohe Tauern National Park where ground surface and near surface temperature is monitored by using miniature temperature dataloggers (MTD). MTD-site DOV-CO (*) was not considered in this study because the nearest sensor to the surface is at 50 cm depth. Substrate: FGM=fine-grained material, CGM=coarse-grained material, BED=bedrock. For locations see Fig. 2.

| Area | MTD-site | Description | Substrate | Elevation | Aspect | Slope | Sensor depth(s) | Data series |
|---|---|---|---|---|---|---|---|---|
| KC | KC-LO | debris above dead ice | CGM | 2690 | 22 | 25 | 0,10,50 | 120906-230812 |
| | KC-UP | debris above dead ice | CGM | 2703 | 12 | 28 | 0,10,20 | 120906-230812 |
| HLC | HLC-LO-S | debris slope | CGM | 2489 | 245 | 32 | 0 | 130906-220812 |
| | HLC-MI-S | debris slope | CGM | 2581 | 268 | 19 | 0 | 130906-220812 |
| | HLC-UP-S | debris slope | CGM | 2696 | 256 | 22 | 0 | 130906-220812 |
| | HLC-LO-N | rock wall niche with debris | BED | 2485 | 47 | 45 | 0 | 130906-220812 |
| | HLC-MI-N | debris slope | CGM | 2601 | 17 | 28 | 0 | 130906-220812 |
| | HLC-UP-N | rock wall niche with debris | BED | 2693 | 45 | 52 | 0 | 130906-220812 |
| | HLC-RF-S | rock face | BED | 2725 | 241 | 75 | 3,10,40 | 110906-220812 |
| | HLC-RF-N | rock face | BED | 2693 | 45 | 85 | 3,10,40 | 110906-220812 |
| | HLC-RT | flat bedrock site | BED | 2650 | 252 | 7 | 3,10,40 | 110906-220812 |
| | HLC-CO | rock glacier sediments | CGM | 2672 | 338 | 8 | 3,10,100 | 230907-220812 |
| | HLC-SO-S | solifluction lobe | FGM | 2391 | 253 | 34 | 0,10,40 | 130906-220812 |
| | HLC-SO-N | solifluction lobe | FGM | 2407 | 34 | 33 | 0,10,40 | 130906-220812 |
| WEI | WEI-LO | rock glacier sediments | CGM | 2652 | 238 | 22 | 0 | 190808-210812 |
| | WEI-MI | rock glacier sediments | CGM | 2662 | 270 | 3 | 0,30,100 | 250907-210812 |
| | WEI-UP | rock glacier sediments | CGM | 2688 | 241 | 7 | 0 | 250907-210812 |
| DOV | DOV-LO-S | debris slope | CGM | 2489 | 220 | 22 | 0 | 250806-200812 |
| | DOV-MI-S | rock wall niche with debris | BED | 2586 | 213 | 19 | 0 | 020906-200812 |
| | DOV-UP-S | debris slope | CGM | 3002 | 166 | 33 | 0 | 020906-300611 & 160811-200812 |
| | DOV-LO-N | debris slope | CGM | 2407 | 342 | 22 | 0 | 020906-200812 |
| | DOV-MI-N | debris slope | CGM | 2501 | 239 | 16 | 0 | 020906-200812 |
| | DOV-UP-N | debris slope | CGM | 2626 | 331 | 25 | 0 | 020906-200812 |
| | DOV-RF-S | rock face | BED | 2628 | 206 | 80 | 3,10,32 | 010906-200812 |
| | DOV-RF-N | rock face | BED | 2638 | 300 | 90 | 3,10,40 | 280906-230711 & 160811-200812 |
| | DOV-RT | flat bedrock site | BED | 2603 | 255 | 14 | 3,10,40 | 140707-200812 |
| | DOV-CO* | rock glacier sediments | CGM | 2606 | 257 | 5 | 100,200,300 | 310708-200812 |
| | DOV-FI | slope with vegetation | FGM | 2644 | 213 | 28 | 0,3,10,30,70,100 | 010906-200812 |
| | DOV-SO | solifluction lobe | FGM | 2578 | 116 | 18 | 3,10,70 | 030906-160810 |
| PAG | PAG-LO | debris slope covered with vegetation | CGM | 2509 | 194 | 37 | 0 | 210906-250812 |
| | PAG-UP | debris slope | CGM | 2628 | 223 | 29 | 0 | 210906-250812 |
| | PAG-BU | summit plateau | CGM | 2932 | 104 | 12 | 0,10,55 | 200907-260811 |
| | PAG-RF-S | rock face | BED | 2216 | 86 | 11 | 3,10,40 | 210906-111107 |
| | PAG-RF-N | rock face | BED | 2255 | 194 | 6 | 3,10,40 | 210906-240812 |
| | PAG-FI | proglacial sandur plane | FGM | 2074 | 120 | 11 | 0,10,75 | 200906-260811 |
| | PAG-SO | solifluction lobe | FGM | 2105 | 342 | 19 | 0,10,55 | 200906-021107 & 070909-260811 |

In total 36 MTDs were installed at the five study areas presented in the previous chapter. The highest MTD site is located at 3002 m a.s.l. (permafrost site), the lowest at 2074 m a.s.l. (seasonal frost). The slope at the MTD sites varies from flat (3°) to vertical (90°). Sensors face all slope orientations. However, most sensors face towards S to W (Fig. 3). At 16 sites 1-channel MTDs are used. At further 20 sites 3-channel MTDs are installed. At one site (DOV-FI) two 3-channel MTDs are used with sensor orientation along a vertical profile. The deepest temperature sensor is located 3 m below ground surface in the open voids of coarse-grained rock glacier sediments. Table 1 gives a detailed picture on the 36 MTD sites. For the present study only the ground surface temperature (GST) data were considered, hence data which were measured at 0 or 3 cm below the ground surface. Therefore data from the site DOV-CO were not considered here because the nearest sensor to the ground surface is located at 1 m depth. Generally, for measuring the GST the respective sensor is located on the ground surface sheltered from direct solar radiation by a thin platy rock allowing air circulation around the sensor.

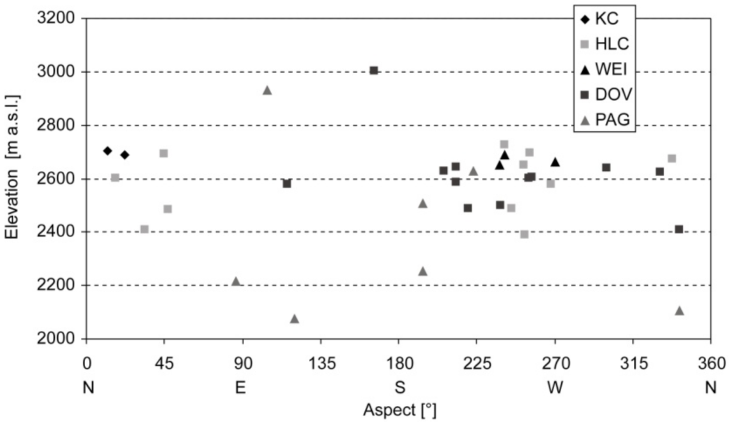


Figure 3: Elevation versus slope aspect for all 36 MTD-sites in the five study areas.

For this study three statistical values were calculated for each GST sites. These are the mean annual ground surface temperature (MAGST), the zero-degree isotherm (ZDI) and the slope of the linear function between mean daily temperature and time (TREND). The MAGST is the mean value for the hydrological year, i.e. October until September of the following year. Most data series end by end of August 2012, hence it was only possible to calculate the MAGST values for five hydrological years spanning 2006-2011. The ZDI is a proxy for permafrost occurrence and was calculated for each sensor using MAGST data and a vertical temperature gradient of 0.0065°C $m^{-1}$. Surface offset and thermal offset are furthermore relevant for the temperature at the top of permafrost below the active layer. These offsets cause generally cooler temperatures at the top of permafrost relative to the ground surface (SMITH & RISEBOROUGH 2002).

The slope of the linear function between daily temperature and time gives a first hint about ground surface temperature evolution. For this analysis all available mean daily data per MTD site were used. A positive slope indicates warming whereas a negative slope cooling.

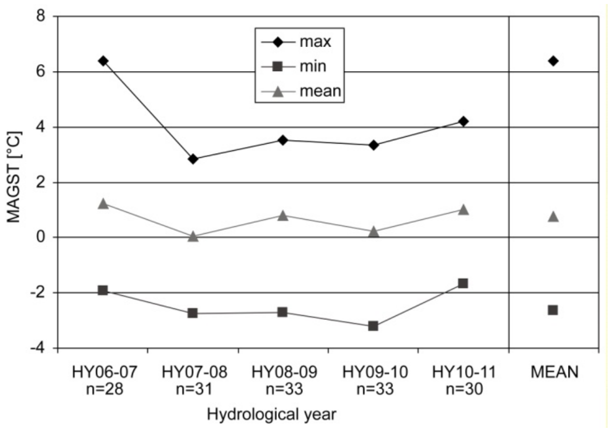


Figure 4: Mean, minimum and maximum MAGST values for each of the five hydrological years as well as the mean value of the five hydrological years based on available MTD-data. Note the differences in available MTD-data for the calculations as indicated by the n-values. Note furthermore the exceptional warm year 2006-2007 as well as a warming tendency after 2007-2008.

## Results and Discussion

The results regarding MAGST clearly show high interannual differences (Fig. 4). The hydrological year 2006-2007 was characterised by an exceptional warm winter half-year causing above-average ground temperatures. At most MTD-sites this was the warmest of all five hydrological years measured so far. In contrast, the following hydrological year 2007-2008 was at many MTD-sites the coldest of all years. After 2007-2008 the MAGST values were generally higher compared to this year. The mean value of all sites was 0.0°C in 2007-2008. In contrast, this mean value was 0.2-1.0°C higher during the following three hydrological years.

A generally warming tendency is also indicated by the TREND analysis for all MTD sites. The analysis on the slope of the linear function for all 36 MTD sites revealed the following results: (a) for two sites data were not adequately available for this calculation (DOV-CO and PAG-RF-S), (b) for three sites no trend is indicated by the data (DOV-UP-S, DOV-MI-N, and DOV-RT), (c) for another two sites a slight tendency towards cooling was revealed (DOV-RF-S and DOV-SO). Finally and most importantly, for 29 sites (80%) a slightly positive trend (slope of linear function varied between 0.0001 and 0.0021) was revealed indicative for ground surface temperature warming (Fig. 5). These calculated slopes of linear function mean that mathematically – and only theoretically – the respective MTD sites warm between 0.0001 to 0.0021°C/day (or 0.04 to 0.77°C/year). However, one has to keep in mind that high interannual variations in the thermal regime are usual as described above and hence even longer times series are necessary to provide more robust trend results.

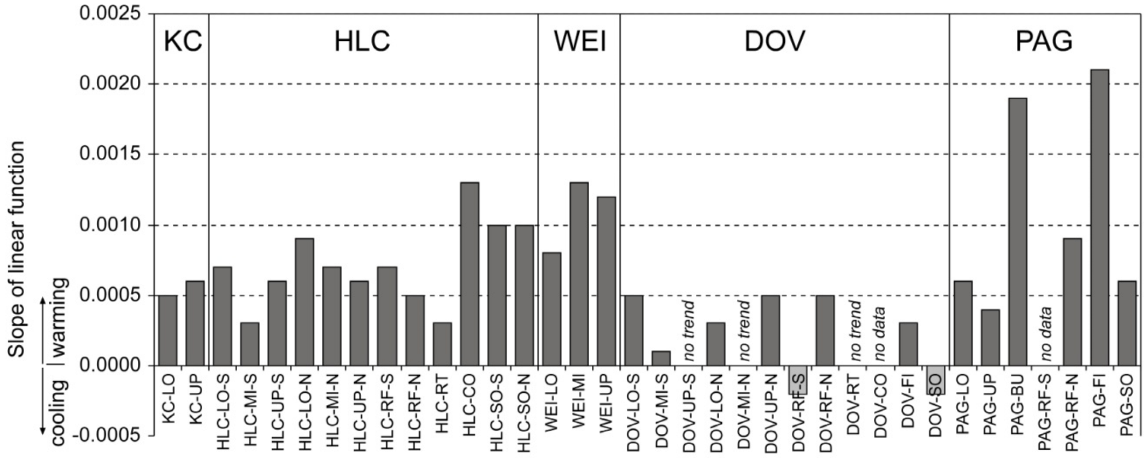


Figure 5: Slope of linear function for ground surface temperature (GST) for all 36 MTD-sites in the Hohe Tauern National Park. The calculated trends are based on all available mean daily temperature data of a given site (see Table 1).

Figure 6 shows two examples of temperature evolution (based on mean daily data) since the beginning of the measurements. One example (HLC-UP-S) reveals a warming trend during the measurement period. This south facing slope located at ca. 2700 m a.s.l. is in a transition from permafrost to seasonal frost. In contrast, the second example reveals no trend at all (DOV-UP-S). The mean ground surface temperature at this south-facing site at ca. 3000 m a.s.l. during the measurement period was -2.6°C, hence a clear – and presumably stable – permafrost site.

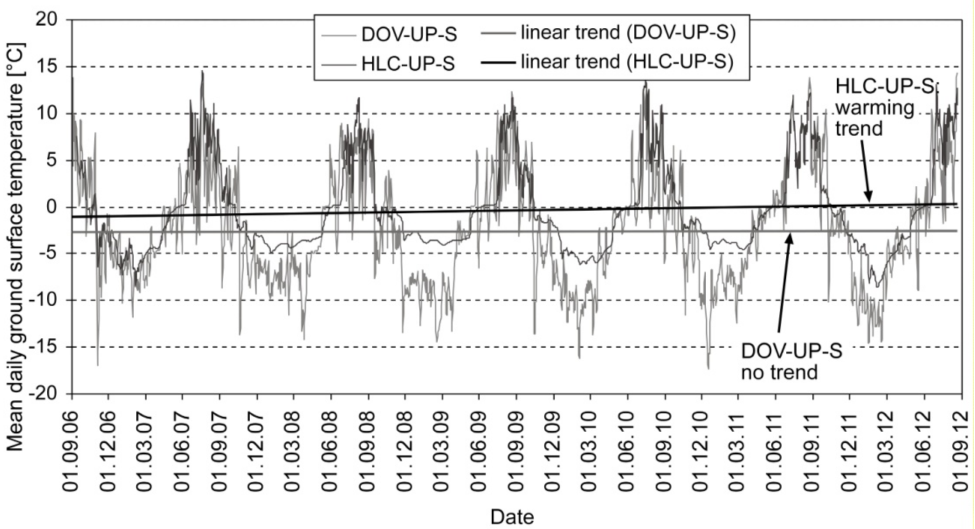


Figure 6: Mean ground surface temperature evolution at two selected MTD sites in the Hohe Tauern National Park. One example indicates no trend and hence warming or cooling of the surface at all (DOV-UP-S), a second example indicates a clear warming trend (HLC-UP-S).

The TREND results strongly suggest a warming trend at most of the sites and in all five study areas of the Hohe Tauern National Park during the last years. Interestingly, this trend seems to be unrelated to snow cover conditions because the MTD sites have big differences in the duration and characteristics of the winter snow cover. The differences in the winter snow cover are indicated by the damping effect of the winter snow cover and the duration of the zero degree isotherm during spring melting as revealed by the available temperature data.

Looking on the distribution in more detail it gets evident that the weakest warming tendency was revealed for the study area in the east (DOV) whereas the strongest warming was calculated for the western-most study areas WEI and PAG. Correlation analyses of the TREND values versus elevation, aspect and slope revealed no clear relationships. Hence elevation, slope and aspect seem to have no influence on the degree of ground surface warming over the last years. Summarising we can conclude that over the last years warming was stronger in the western part of the national park relative to the eastern part influencing all elevations above c.2000 m a.s.l., all slope inclinations, all aspects and unrelated to winter snow cover conditions.

The ZDI approach allows the calculation of all MTD sites to one reference. The differences of the calculated ZDI for each site revealed strong interannual variations with high values for 2006-2007, 2008-2009 and 2010-2011, whereas low values for 2007-2008 and 2009-2010. Obviously this distribution is very much linked to the MAGST values. The box-plot diagram in Fig. 7 clearly shows the exceptional high elevation values for 2006-2007. However, the median values for the ZDI of the two hydrological years 2008-2009 and 2010-2011 where even higher with, respectively 2715 and 2768 m a.s.l.

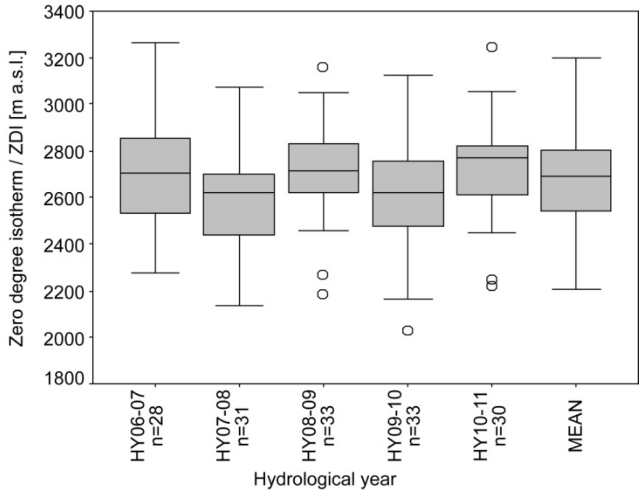


Figure 7: Box plot diagram of the variation of the ZDI for the five hydrological years as well as the mean ZDI values. Outliers are indicated by circles. Note the highest median value for 2010-2011

In Figure 8 the mean ZDI-values per site where plotted against slope aspect in order to analyse and visualise the influence of slope orientation on the elevation of the mean ZDI during the five hydrological years 2006-2011. Furthermore a polynomial function was calculated showing nicely that the ZDI is generally higher in south-facing slopes compared to east- and west- as well as north-facing slopes. This pattern is related to insulation (north-south) as well as cloudiness (east-west) effects. The same calculations where made for the single year data. Results for each hydrological year, each aspect class and mean and range values are listed in Table 2.

As explained above, the mean ZDI values over the last years indicate to some extent also the lower limit of permafrost in the National Park Hohe Tauern although surface and thermal offsets certainly influence these limits. The calculations reveal ZDI elevations of 2821 m a.s.l. for south facing slopes. For north facing slopes a 350 m lower ZDI value was calculated. The calculated mean ZDI for east facing slopes is 55 m higher compared to west facing-slopes (2747 vs. 2692 m a.s.l.) hence they are in between the values for north- and south-facing slopes as expected. These results further imply that permafrost at south facing slopes can be expected above c.2820 m a.s.l., whereas on north-facing slopes permafrost might occur to elevations even below 2500 m a.s.l.

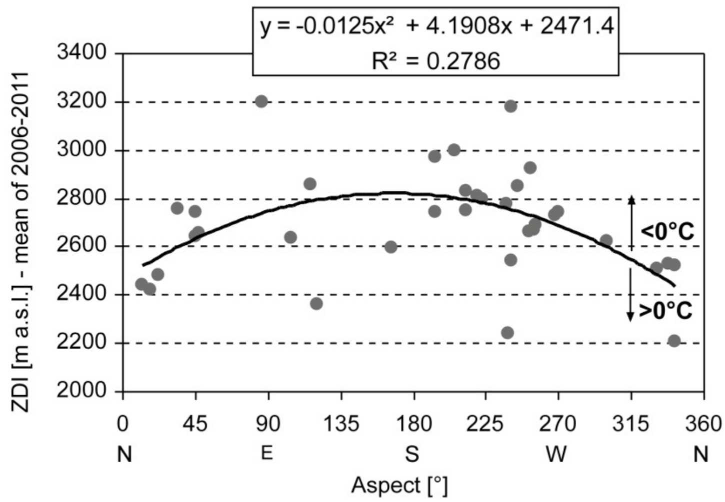


Figure 8: Calculated mean ZDI of the five hydrological years 2006-2011 versus slope orientation for all MTD-sites with GST data. The depicted polynomial function indicates where GST are expected to be above or below 0°C and hence to some extent is indicative for presence or absence of permafrost.

Interestingly the interannual variation in the elevation of the ZDI is substantially smaller at north-facing slopes (only 116 m) compared to the other three main aspect classes. The highest variation in the ZDI was calculated for south-facing slopes with 168 m (Table 2). This indicates that warm years influence to a higher extent warmer, south-facing slopes compared to cooler, north-facing slopes where thermal conditions seem to be more stable.

## Conclusions

From the above considerations the following conclusions can be drawn:

Continuous ground surface temperature data with hourly resolution were available for this study from five different study areas in the Hohe Tauern National Park. Data series covered the time span of up to September 2006 to August 2012. These data represent some of the longest continuous time series of ground temperature in the periglacial environment of central Austria and are valuable for understanding permafrost distribution and future changes.

The first measurement year (hydrological year 2006-2007) at the 35 MTD sites with ground surface in the Hohe Tauern National Park was unusually warm and the warmest of all five years with available data. On average ground surface temperatures were 1.2°C warmer compared to the coldest year (2007-2008) and still 0.2°C warmer to the second warmest year (2010-2011). Generally, MAGST values increased since 2007-2008.

Trend analyses of 2006-2012 data showed that in 80% of all MTD sites a clear warming trend was revealed. This warming trend is strong and consistent at the four study areas located in the western part of the national park (Schober and Glockner Mountains). Contrary, in the Ankogel Mountains located in the very east of the national park territory this trend is substantially weaker with MTD sites showing either no trend at all or only weak warming trends. Differences in elevation, slope, aspect and winter snow cover characteristics at the MTD sites seem to have no influence on the degree of ground surface warming over the last years.

The ZDI is a rough proxy for absence or presence of permafrost although surface and thermal offsets as well as high ground temperature variability within short distances in relatively homogenous terrain make permafrost prediction very difficult in sporadic and discontinuous permafrost areas. The analysis of the ZDI revealed again strong interannual variations. Based on polynomial functions, the mean ZDI for the five hydrological years 2006-2011 was calculated for each of the four main slope aspect directions. Results show that permafrost at south facing slopes can be expected above c.2820 m a.s.l., whereas on north-facing slopes permafrost might occur to elevations even below 2500 m a.s.l. The lower limit of permafrost on east-facing slopes is in the order of 50 m higher compared to west-facing slope. This is presumably related to cloudiness effects (no convection clouds in the morning and hence stronger insulation compared to the afternoon on east-facing slopes).

Finally, the results indicate that warm years influence to a higher extent warmer, south-facing slopes relative to cooler, north-facing slopes where thermal conditions seem to be more stable. Warmer years will occur more often in future as indicated by climate model scenarios. This could imply for instance rock fall events in periods which are currently thought to be safe for man and animals in the high mountains of Hohe Tauern National Park.

Table 2: The calculated ZDI for the different hydrological years and slope aspects based on polynomial functions of ZDI vs. aspect. Furthermore, the calculated mean ZDI as well as the ZDI range for each aspect class are listed.

| Period | Aspect | | | |
|---|---|---|---|---|
| | E | S | W | N |
| ZDI of HY06-07 [m a.s.l.] | 2794 | 2888 | 2744 | 2461 |
| ZDI of HY07-08 [m a.s.l.] | 2640 | 2721 | 2607 | 2365 |
| ZDI of HY08-09 [m a.s.l.] | 2749 | 2829 | 2725 | 2486 |
| ZDI of HY09-10 [m a.s.l.] | 2685 | 2751 | 2615 | 2416 |
| ZDI of HY10-11 [m a.s.l.] | 2793 | 2886 | 2760 | 2481 |
| *mean ZDI [m a.s.l.]* | *2747* | *2821* | *2692* | *2471* |
| *range ZDI [m]* | *153* | *168* | *153* | *116* |

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