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Using Borehole Temperatures for Knowledge Transfer about Mountain Permafrost: The Example of the 35-year Time Series at Murtèl-Corvatsch (Swiss Alps)

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Introduction: Background

1 In a warming world, mountains warm up. This is critical where they are affected by surface and subsurface ice. The rapid shrinking of glacier ice is easily recognisable at the surface and thus understandable. It has been documented internationally for over a century and has already been an icon of human-induced climate change for decades (Zemp *et al.*, 2015). Its consequences for landscape evolution, the water cycle and related surface processes are discussed in a rich scientific literature, in politics and by the public (Haeberli *et al.*, 2022). In strong contrast to the widespread awareness

concerning surface ice, the existence of subsurface ice contained in permafrost slopes of cold mountains has long not been realistically perceived by scientists, decision makers, and the public at large, although the effects of its warming and degradation may be equally far-reaching.

2 First systematic investigations using adequate facts and physics-based concepts of permafrost science for cold mountains only started a few decades ago. The primary focus was, and still is, on viscous creep phenomena in ice-rich frozen talus/debris, the so-called "rock glaciers" (Wahrhaftig and Cox, 1959; Barsch, 1969; *cf.* Haeberli *et al.*, 2006, Cicoira *et al.*, 2021), and on stability aspects related to steep frozen bedrock slopes (Haeberli *et al.*, 1997; Davies *et al.*, 2001; Gruber and Haeberli, 2007; Krautblatter *et al.*, 2013; Etzelmüller *et al.*, 2022). Dealing with permafrost has since become an advanced interdisciplinary, climate-related field of mountain research, especially in Europe (*cf.* Harris *et al.*, 2009; Haeberli *et al.*, 2010; Bodin *et al.*, 2015; Etzelmüller *et al.*, 2022). It thereby became increasingly clear that continued warming (PERMOS, 2023) and destabilisation of permafrost slopes in cold mountains on Earth is a severe long-term impact and deserves commitment.

3 As part of this important ongoing activity and progress, Philip Deline has built up an internationally recognised research unit carrying out pioneering work on characteristics, processes and climate-change impacts related to the coldest, steepest, highest and logistically most challenging mountain belts. The state-of-the-art review by world-leading experts on "Ice loss from glaciers and permafrost and related slope instability in high-mountain regions" (Deline *et al.*, 2021) as well as a continued series of unique specific publications on the topic (e.g., Ravanel and Deline, 2010; Bodin *et al.*, 2015; Magnin *et al.*, 2015, 2017; Ravanel *et al.*, 2017, 2023) document the precious contribution accomplished by the "Chambéry team". The following thoughts are devoted to Philip in recognition of, and gratefulness for this admirable achievement.

From Reality to Minds

4 The physical reality is simple, logical and easily comprehensible: mean annual air temperature at high-enough altitude is negative and so is mean annual surface temperature of mountain slopes exposed to such negative air temperatures. It is indeed remarkable that this elementary condition of physical meteorology/geoscience and, hence, the existence of permafrost in cold mountains had long hardly been recognised even in science. This situation, still today, often continues to constitute a major challenge: permafrost in cold mountains is widespread and a fundamental part of the high mountain cryosphere. Nevertheless, its existence is much less present in the minds of many, quite often including scientists from other disciplines, stakeholders, or policymakers. Communication about mountain permafrost is therefore often difficult due to the absence of awareness about the phenomenon. The primary reason seems evident: For most people on Earth, permafrost as a subsurface phenomenon is not visible, not a part of their personal experience, and therefore tends to escape basic reflections. Furthermore, the phenomenon of perennially frozen subsurface materials in cold mountains is probably absent in many curricula of geoscience education. In high-mountain hazard assessment work subsurface thermal conditions are often not yet taken into adequate consideration. International efforts have therefore been undertaken (GAPHAZ, 2017; Allen *et al.*, 2022) to overcome this important deficit.

Especially in practical consulting and policy-related work, knowledge transfer concerning mountain permafrost can play a key role.

Figure 1

Active rock glacier Murtèl-Corvatsch from the Corvatsch cable car. At the drill site (red circle), massive ice (about 90 vol%, specific electrical resisitivity about 2 MΩm) from frozen avalanche deposits occurs between 5 and 28 m depth. Most of the overall movement takes place within a shallow shear horizon consisting of frozen fine material below this massive ice at 28 to 30m depth. Further down to bedrock at about 56 m, ice-saturated blocks exist and undergo zero creep.

Photograph W. Haeberli.

5 Knowledge and understanding about mountain permafrost relate to basic physical but to some degree also abstract concepts, which must as far as possible be supported by measured facts. Measuring those facts about thermal conditions inside remote mountain slopes, on the other hand, requires respective know-how and experience. In addition, the considerable technical and financial resources needed only allow measurements at a limited number of sites (Noetzli *et al.*, 2021). Here, we refer to permafrost temperatures recorded in a borehole through an ice-rich, active rock glacier at the Murtèl-Corvatsch site in the eastern Swiss Alps. Historically, drilling and initiating long-term borehole observations at the Murtèl-Corvatsch site in 1987 (Figures 1 and 2; Haeberli *et al.*, 1988, 1998) at that time marked an initial step towards more widespread recognition of the existence and climate-related aspects of mountain permafrost in science as well as in the public. Vonder Mühll and Haeberli (1990) and Vonder Mühll *et al.* (1998) presented first detailed analyses of the obtained permafrost temperatures. Due to cumulative deformation resulting from viscous creep (rock glacier flow), the borehole had to be re-drilled in 2015 at the same site, allowing careful intercomparison of overlapping borehole temperatures in the two boreholes (PERMOS 2019). The full data set covering more than 30 years of continuous

temperature data is available from the Swiss Permafrost Monitoring Network (PERMOS; https://www.permos.ch/). Etzelmüller *et al.* (2020) summarise and discuss these observations within the wider framework of permafrost temperature monitoring following the internationally coordinated project "Permafrost and Climate in Europe" (PACE; *cf.* Harris *et al.*, 2009). These recent scientific analyses clearly show that the general developments observed at the Murtèl-Corvatsch site are quite representative at regional to continental scales. The Murtèl-Corvatsch borehole temperatures today indeed constitute a key time series used in global assessment reports like Hock *et al.* (2019) or Biskaborn *et al.* (2019), the annual reports (Noetzli *et al.*, 2022) by the Global Terrestrial Network for Permafrost (GTN-P), or global reviews like Smith *et al.* (2022).

Figure 2

Drilling installation in 1987 (top left) and 2015 (top right), recovered core material from the 2015 redrilling (bottom left) and current drill-site instrumentation for long-term monitoring (bottom right). In 1987 (top left), the spring snow cover was used to reduce the temperature of the air from the compressor (foreground) to the air-cooled drilling (background). Redrilling in 2015 became necessary because of cumulative borehole deformation inside the creeping frozen body.

Photographs by W. Haeberli (upper left) and Jeannette Noetzli.

Key Messages Out of 35 Years of Permafrost Monitoring

6 The now 35-year time series from the Murtèl-Corvatsch borehole temperatures (Figures 3 and 4) is used in the following to illustrate—in plain language to be used on such occasions—possibilities of deducing most important and clear key messages on mountain permafrost for people and partners not yet familiar with the subject. The emphasis here is on "frequently asked questions":

7 How cold is mountain permafrost?

8 What influences temperatures of mountain permafrost?

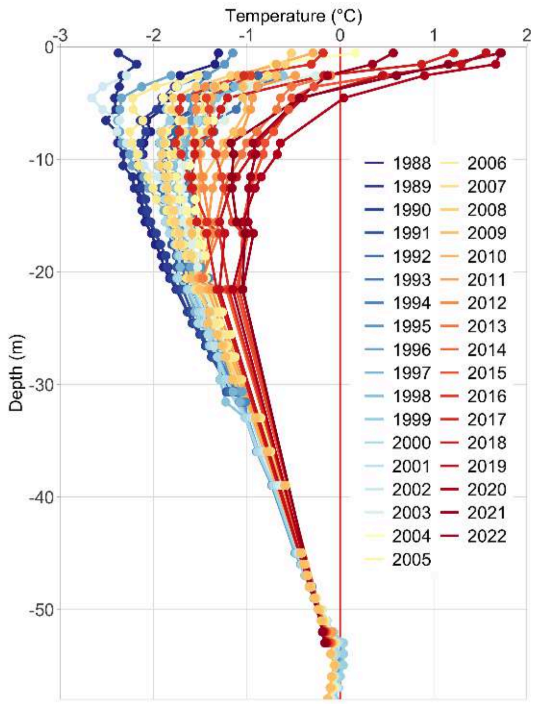
9 How deep does mountain permafrost reach below the surface?

10 What are past and future effects from a warming Earth on mountain permafrost?

11 How does warming and thawing affect slope stability in mountain permafrost?

12 These questions (labelled A to E further below) are treated using ten answers or "Key Messages" (*numbered and in italics*). These Key Messages form the basis for better knowledge transfer and communication with, for instance, authorities, stakeholder, or media representatives. The primary issue relates to the didactics of scientific outreach concerning climate change impacts on cold mountains.

Figure 3



Annual mean temperature profiles at the Murtèl-Corvatsch drill site from 1988 to 2022. Source: PERMOS 2022. Seasonal fluctuations predominate above about 10 m depth. Note the systematic warming trend down to tens of meters depth. Permafrost continues in bedrock to even greater depth below the bottom of the borehole.

Question A: How Cold Is Mountain Permafrost?

13 The borehole temperatures measured at Murtèl-Corvatsch below the uppermost 10-meter depth cover a range of about 0 to –3 °C. They document that the corresponding subsurface materials are indeed—and have so far remained—frozen throughout the years. This is the thermal condition which defines the technical term "permafrost" (short from "permanent frost"). The temperature range observed in the Murtèl-Corvatsch borehole is close to the mean annual air temperature (–1.66 °C for the period 1997 to 2018, Hoelzle *et al.* 2022) at the altitude (2670m a.s.l.) of the site. Such

temperature conditions are representative for many occurrences of permafrost in mid-latitude mountain ranges:

> *Key Message 1. Important parts of mountain permafrost are relatively "warm", having subfreezing temperatures close to 0 °C (i.e., between -2 °C to 0 °C); considerably colder permafrost exists in shady and steep slopes at the highest peaks of cold mountains.*

14 Ground temperatures vary with time and depth. The amplitudes of the variations with time decrease exponentially with increasing depth. Seasonal fluctuations of surface temperature penetrate down, and diminish to less than 0.1 °C, at about 15 to 20 m below the surface. High summer temperatures thereby induce thawing of the uppermost few meters (the so-called "active layer") where annual freeze-thaw cycles take place. The existence of such a thawed near-surface layer during the warm periods of the year prevents easy and direct recognition of frozen conditions at depth from visual inspection and surface measurements alone.

15 Over the entire 35-year measurement period, as well as over the entire documented depth profile, temperatures at depth systematically increased (Figures 3 and 4). At 15 to 20 m depth, where the amplitude of seasonal fluctuations approaches zero, permafrost warmed from −1.8 to −1.0 °C. This corresponds to a 2–3°C centennial warming trend. Similar warming trends are observed in other high-altitude and high-latitude boreholes in permafrost with subzero temperatures (Biskaborn *et al.*, 2019; Smith *et al.*, 2022):

> *Key Message 2. Mean annual ground temperatures at 15 to 20 m depth in mountain permafrost are rising at rates which are comparable with rates of global atmosphere and permafrost warming.*

16 No significant temperature differences between the years 1988 and 2022 occurred at depths between about 40 to 50 m below surface:

> *Key Message 3. Effects of rapid atmospheric warming during the past few decades reach tens of meters deep below surface but have not yet arrived at greater depths.*

Question B: What Influences Temperatures of mountain Permafrost?

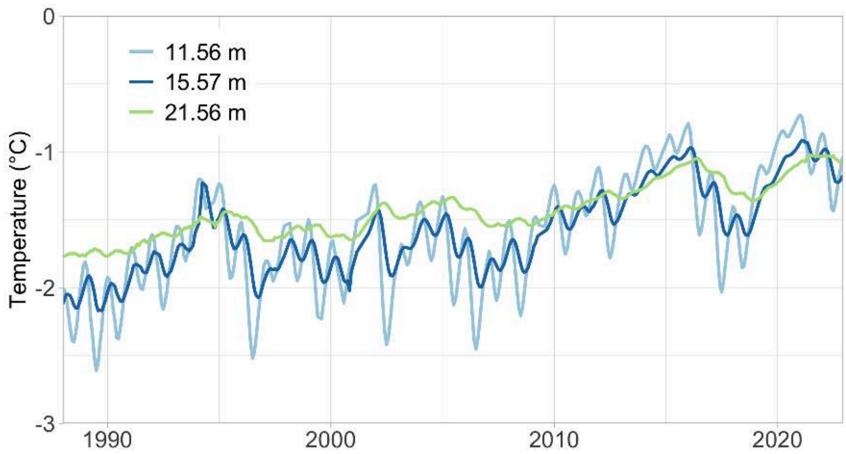
17 The Murtèl-Corvatsch borehole temperatures measured at shallow depths, i.e., some 10 m below surface, not only closely correspond to mean seasonal and annual air temperatures at the site but also generally follow their changes in time:

> *Key Message 4. Air temperature is — in a first approximation—the primary factor determining the occurrence in space and evolution in time of mountain permafrost.*

18 This fact together with measured or modelled climate data is used in numerical models to predict probabilities of occurrence of mountain permafrost at large spatial scales (Gruber, 2012; Obu *et al.*, 2019). At regional spatial and shorter temporal scales, additional effects come into play. Sunny slopes, for instance, are warmer than shady

ones. Moreover, the temperature time series at Murtèl-Corvatsch in the uppermost about 10 m below surface reveals sharp “cold peaks” during snow-poor winters. Snow depth in early winter (November and December) indeed governs the winter and spring subsurface temperature regime. Thick winter snow cover with its high-air content efficiently insulates the ground from losing heat during the cold season. The absence of thick and continuous snow during dry early winters on the other hand cause intense subsurface cooling and especially cold conditions. Examples documented in the Murtèl-Corvatsch time series are the winters of 2001/2002, 2005/2006, 2015/2016 or 2016/2017. The same cooling effects also occur at sites with snow being removed by wind erosion, like on exposed ridge tops, or where snow becomes trapped between coarse blocks like at the surface of the Murtèl-Corvatsch rock glacier.

Figure 4



Evolution of borehole temperatures between 1987 and 2022 at three selected depths below surface. Source: PERMOS 2022. Note the systematic decrease in annual temperature amplitude with increasing depth, the marked short-term varibility, and the overall warming trend through time.

19 The effect of a late arrival of the snow cover with intense cooling of the ground down to more than 20 m was particularly visible in 2015/2016 and 2016/2017. Enhanced warming, on the other hand, took place in spring 2022 due to early snow melt in spring at high elevations (PERMOS 2023), enabling energy to penetrate the ground for much longer than if snow had melted later. Such observed examples document that snow conditions can interrupt or accelerate a general warming trend. In contrast, variable incoming solar radiation primarily influences spatial permafrost distribution patterns but exerts little effect on its evolution in time. Hence,

> *Key Message 5. Incoming solar radiation and effects of winter snow characteristics are locally modifying factors in rugged topography; early- and late-winter snow conditions have a strong influence on thermal variations with time. But steep rock walls with thin or no snow follow air temperatures closely.*

Question C: How Deep Does Mountain Permafrost Reach Below the Surface?

20 Mean surface temperature and the warm interior of the Earth set the two boundary conditions related to the depth reached by perennial freezing. The colder the surface, the deeper permafrost reaches below surface. As a rule of thumb and assuming conditions of thermal equilibrium, permafrost thickness is about 30 to 50 m per negative degree centigrade of the mean annual surface temperature. As an effect of deep thermal disturbance by global warming, permafrost thickness in mountainous regions today in most cases reaches values over 100 m per negative degree centigrade of mean surface temperature (*cf.*, Etzelmüller *et al.*, 2020). As an example, a present-day mean near-surface temperature of −2 °C can relate to a total permafrost thickness well over 100 meters:

> *Key Message 6. Permafrost with negative temperatures close to 0 °C typically reaches tens of meters depth while cold permafrost with temperatures below about −3 °C can be expected to reach depths of hundreds of meters.*

21 Sharp and high-altitude mountain peaks like the Matterhorn in the Swiss Alps can be completely frozen through (Noetzli and Gruber 2009).

22 An interesting thermal anomaly can be observed at about 55 m depth in the Murtèl-Corvatsch borehole. At this depth, the temperature reaches 0 °C but at greater depth becomes negative again. Small seasonal temperature variations indicate circulation of water during summer along a thin, confined unfrozen layer or channel within the permafrost, the total depth of which is estimated at about 100 m (Vonder Mühll, 1992). The thin unfrozen intra-permafrost layer, a so-called talik, at depth in the Murtèl-Corvatsch permafrost documents that

> *Key Message 7. Unfrozen water can exist in frozen rocks with near-thawing temperatures and cause marked thermal anomalies.*

Question D: What Are Past and Future Effects of a Warming Earth on mountain Permafrost?

23 As we know from everyday experience, changes in surface temperature penetrate to deeper parts of massive bodies. Deep warming and finally degradation of permafrost, therefore, represent the primary effect of ongoing atmospheric temperature rise. In perennially frozen materials without freely circulating water, warming at depth as a consequence of surface warming primarily takes place through heat conduction. This is a very slow and inexorable process. Warming effects in permafrost since the end of the Little Ice Age around 1850 until today have reached depths of around 100 m below surface (Noetzli and Gruber, 2009) and continue propagating steadily with an exponential decay of the amplitude towards even greater depths. Even in an unlikely scenario without further surface warming, such warming at depth will continue at centennial time scales:

Key Message 8. Continued warming of mountain permafrost to depths of 100 m and more is physically predetermined as an unavoidable long-term phenomenon for at least a century or two.

24 Thawing of frozen, ice-bearing rock materials including the formation of unfrozen water within still frozen parts starts where temperatures rise closer to 0 °C. Ice melt takes place as a quick reaction to rapid warming at the top of permafrost, increasing the thickness of the active layer at the surface, and as a slow and strongly delayed response to warming at depth. It absorbs large amounts of energy and, thereby, induces further retarding effects. At depth, the energy provided by the weak, constant heat flux from the interior of the Earth, the geothermal heat flow, can annually melt an ice thickness at about the centimeter scale, while near-surface heat from rapidly warming surfaces induces higher heat fluxes and tends to melt ice thicknesses at a centimeter to decimeter scale per year. Depending on initial thermal conditions, surface warming rates and ice contents, annual rates of permafrost thaw are characteristically in the order of centimeters to a few decimeters per year (Zhao *et al.*, 2022). Complete thaw involves centennial time scales for shallow ice-bearing permafrost and millennial time scales for thick ice-bearing permafrost. At some point of the melting process by heat conduction, circulating water (heat transport) along preferential flow paths (e.g., clefts) can kick in and accelerate the melting rate (Hasler *et al.*, 2011). Cold and deep permafrost in the highest mountain peaks is unlikely to completely thaw even in extreme scenarios of human-induced warming. This is in striking contrast to the rapid vanishing of glaciers and smaller features of surface ice. However, remaining permafrost zones will tend to further warm and destabilise in future:

Key Message 9. Permafrost inside cold mountain slopes and icy peaks with annual surface temperatures well below 0 °C will continue to exist—even though under conditions of strong and deep thermal disturbance—when most mountain glaciers are likely to have long disappeared already.

Question E: How Does Warming and Thawing Affect Slope Stability in Mountain Permafrost?

25 A common perception is that ice in frozen materials acts like a “glue” or “cement”, keeping fractured rocks or individual rock particles together. This is not totally wrong, but not the primarily relevant mechanism either. The strength of ice is limited by the fact that it can, in particular circumstances, quite easily deform. Furthermore, the ability of ice to deform markedly increases with increasing temperature. Warming up perennially frozen slopes containing ice makes the rock-ice mixture “softer”, less resistive against the driving force of gravity (Davies *et al.*, 2001; Krautblatter *et al.*, 2013). This effect tends to be reinforced by the presence of increasing amounts of liquid water within the ice at temperatures close to 0 °C. The consequences are evident.

26 Perennially frozen masses of talus or debris with high ice contents—mostly far in excess of the pore volume of the rock material—have been creeping down-valley for millennia, often leading to the formation of spectacular, lava stream-like landforms called “rock glaciers”. Especially the lower parts of these creeping masses with “warm

and warmed-up" permafrost have recently strikingly accelerated their creep rates (e.g., Daanen *et al.*, 2012; Eriksen *et al.*, 2018; Cicoira *et al.*, 2020; Kääb *et al.* 2021; Kummert *et al.*, 2021; *cf.* continued monitoring by PERMOS; Pellet *et al.* 2021) due to the pronounced temperature rise and higher water contents (Kenner *et al.*, 2020), often from characteristic values of decimeter/year to meter/year (PERMOS 2023) and in places exhibiting striking phenomena of instability (Hartl *et al.*, 2022).

27 Advanced laboratory experiments using the centrifuge technology provides qualitative and quantitative information about the stability of frozen rocks with ice-filled clefts (Davies *et al.* 2001). The stability strongly varies with changes in subfreezing temperatures: It is high at −5 °C but decreases with warming, yet still negative temperature. Thereby, the strength not only of the ice and related ice-rock contacts is affected but also of the rock itself with its rock-to-rock contacts (Krautblatter *et al.*, 2013). At temperatures between about −1 to 0 °C, stability reaches a minimum that is even lower than at positive temperatures. In such "warm", near zero-degree centigrade permafrost, combinations of, and interactions between, rock, ice and liquid water develop. Increasing amounts of unfrozen water, increased water pressure or fast advective heat flow to larger depth (Hasler *et al.* 2011) along previously ice-filled rock joints importantly contribute to critical weakening. After complete thaw to unfrozen state, such particularly critical conditions vanish and stability slightly increases again but by far not to the level induced through cold permafrost (Davies *et al.*, 2001). A remarkable frequency of large rock-ice avalanches from warm permafrost slopes indeed occurred during the past few decades (for example, Carey *et al.*, 2012, Phillips *et al.*, 2016; Walter *et al.*, 2017; Coe *et al.*, 2018; Shugar *et al.*, 2021; Vilca *et al.*, 2022). Permafrost temperatures measured in boreholes document the warming trend at depth, which is most probably responsible for this development, and which will continue in a largely predetermined way for an extended future as shown by numerical model calculations (Noetzli and Gruber, 2009):

> *Key Message 10. The high stability of permafrost slopes in cold mountains is already today reduced due to deep warming and will continue to decrease over centuries to come.*

28 Especially delicate situations develop where glacier retreat adds to slope destabilisation through glacial de-buttressing, and additionally leads to the formation of new lakes at the immediate foot of steep perennially frozen icy peaks. The existence and new formation of such lakes involve the potential of far-reaching floods from rock-ice avalanches impacting such mobile water bodies (Haeberli *et al.* 2017, Allen *et al.*, 2022).

Perspectives

29 Within the 35 years of borehole temperature monitoring at the Murtèl-Corvatsch site, climate-related interdisciplinary research on mountain permafrost has made rapid, essential, and urgently needed progress. Permafrost is a fundamentally important subsurface phenomenon not only of the polar regions but also of cold high mountains at mid-latitudes. Thermal conditions in permafrost regions are already today deeply and severely disturbed by global warming (Biskaborn *et al.*, 2019). Continuation and further expansion of this disturbance and imbalance is largely predetermined for generations to come. The consequences, especially with respect to slope stability and

catastrophic mass movements, constitute a strong impact from climate change on cold mountains on Earth and a severe challenge to be faced with the aid of the best available knowledge and process understanding. The ongoing program of monitoring ground temperatures in mountain permafrost as part of global climate observation (Streletskiy *et al.*, 2021) provides the basis for improving this necessary knowledge and understanding of science, in the public and among decision makers.

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ABSTRACTS

Climate-related permafrost is widespread in cold mountains and heavily affects slope stability. As a subsurface phenomenon, however, it is often still absent in the perception of key partners concerning the discussion and anticipation of long-term impacts on high mountain regions from continued global warming. Outreach and knowledge transfer, therefore, play a key role.

Long-term observations of permafrost temperatures measured in boreholes can be used to convey answers and key messages concerning thermal conditions in a spatio-temporal context, related environmental conditions, affected depth ranges, and impacts of warming and degradation on slope stability.

The 35-year Murtèl-Corvatsch time series of borehole temperatures from which data is available since 1987, is used here as an example. Today, mountain permafrost is well documented and understood regarding involved processes, as well as its occurrence in space and evolution in

time. Thermal anomalies caused by global warming already now reach about 100 meters depth, thereby reducing the ground ice content, causing accelerated creep of ice-rich frozen talus/debris (so-called “rock glaciers”) and reducing the stability of large frozen bedrock masses at steep icy faces and peaks.

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Keywords: permafrost, mountains, climate change, borehole temperature, slope stability

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