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Impacts of Global Warming on Mountaineering: A Classification of Phenomena Affecting the Alpine Trail Network

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The high Alpine landscape is significantly shaped by glacial and periglacial processes. It is sensitive to effects caused by global warming, such as glacier retreat and permafrost degradation. Trails and mountain huts form the infrastructure basis for hiking and mountaineering in the Alps. This infrastructure is a decisive factor for summer mountain tourism. This article presents a classification of phenomena describing the effects of global warming on high Alpine trails and routes. The classification was developed based on an in-depth study in the Austrian Alps. The examples collected show that in the context of global warming, numerous different types of phenomena can affect both the occurrence of natural hazards along high Alpine trails and routes, and the accessibility of the terrain. Depending on the specific situation, threats and difficulties can increase or decrease. Trail holders have to adapt the high Alpine trail network to these changes. The classification presented here can serve to support maintenance of the Alpine trail network in the future.

Keywords: *Global warming; glacier retreat; Eastern Alps; trail network; summer mountain tourism; hiking; natural hazards; infrastructure management; Austria.*

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Introduction

The high Alpine landscape has been and still is significantly shaped by glacial and periglacial processes and is therefore highly sensitive to effects caused by global warming, such as glacier retreat and permafrost degradation (eg Haeberli and Beniston 1998; Fischer et al 2006). Mountaineering as an important tourist activity in the European Alps can be indirectly affected by an increase in the occurrence of natural hazards, such as rockfall, debris flows, or landslides (eg Haeberli 1999; Harris et al 2001; Gruber et al 2004).

Trails and mountain huts form the infrastructure basis for hiking and mountaineering in the Alps and are therefore a decisive factor for summer mountain tourism (Muhar et al 2006). Institutions responsible for trail maintenance and safety have pointed out a steadily increasing number of problem situations and growing financial expenses for trail maintenance (Kapelari 2008).

In this article we present a classification of phenomena describing effects of global warming on trails and routes from a mountaineering perspective. These phenomena usually arise from the spatial coincidence of morphodynamic processes, specific landforms, and trail infrastructure. The classification is intended as a basis for developing adaptation strategies.

Study area

Our study focused on the Austrian Alps, where the lowest glacier tongues are situated at an altitude of about 2100 m and periglacial processes occur from approximately 2000 m upwards. In this article, therefore, we use the term "high Alpine area" to refer to terrain from 2000 m upwards in glaciated mountain ranges in the Eastern Alps and the term "high Alpine trail network" to refer to trails and routes in this area.

The term "trails" refers to marked and regularly maintained hiking trails. They may also include sections where fixed ropes or similar technical devices are installed as safeguarding measures. We use the term "routes" to refer to other, usually unmarked ascents, in particular on glaciers. While they cannot be regarded as part of the trail infrastructure in a narrower sense, they often play an important role for mountaineering in high Alpine terrain and are thus also depicted on hiking maps.

The major part of the Alpine trail network in Austria is maintained by mountaineering associations. The most

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relevant trail maintainers are the Austrian Alpine Club (OeAV) and the German Alpine Club (DAV). Together, they are responsible for about 40,000 km of trails. According to the Austrian Civil Code, the responsibility of a trail holder usually implies a legal liability for accidents caused by neglectful maintenance. Although maintenance work is often done by volunteers, these associations report annual costs of about € 2 million (US$ 2.6 million; see Witty 2007).

Data collection

The classification of phenomena presented here is based on a systematic collection of examples using a wide range of sources:

- Scientific literature and mountain sports literature;
- Evidence from mountain guide books and mountain sports websites and web forums;
- Qualitative expert interviews with trail maintainers, glaciologists, and mountain guides ($N = 8$);
- Field mapping in seven high Alpine mountain ranges, representative for the spectrum of landscapes with Alpine trail networks in the Austrian Alps (extent of glaciation, geographical location, geology, relevance for tourism);
- Ad hoc remarks of local case actors during field mapping.

We implemented a theoretical sampling approach (Rosenthal 2008), continuing data collection until a theoretical saturation was reached, that is, until no additional data could be found which would have heightened the informative value of the existing categories. This sampling method was useful for identifying categories; however, it did not provide any quantitative information on the frequency of occurrence or on the spatial distribution of the phenomena.

In line with our research objective we classified the phenomena according to their effects on trails and routes and their consequential relevance for mountaineering. This does not necessarily correspond to the usual approach in the geosciences, where phenomena and events are mostly classified according to the underlying geomorphological processes, such as mass wasting and glacial or fluvial processes.

Results

This classification distinguishes two main groups of phenomena with different effects on trails and routes: (1) changes in the occurrence of natural hazards and (2) changes in the accessibility of the terrain. Changes in the occurrence of natural hazards in the context of global warming are addressed in a considerable body of existing scientific literature (eg Haeberli et al 1989; Ballantyne 2002; Nötzli et al 2004; Fischer et al 2006). Less attention has been given so far to the accessibility of the terrain and the technical difficulty of high Alpine trails and routes, despite their relevance to mountaineering. We aim to contribute to filling this gap by focusing on these aspects in this article.

In the following paragraphs and tables we describe the relevant phenomena and illustrate some practical examples. For a detailed mapping of the phenomena in selected mountain ranges see Braun (2009).

Changes in the occurrence of natural hazards

Introductory considerations: High Alpine environments are areas of strong erosion and mass movements. Combined with the presence of humans or the construction of infrastructure, these natural processes can cause damaging events and are therefore perceived as potential "natural hazards."

In the context of mountaineering, the term "natural hazard" usually refers to fast mass movements such as rockfall, debris flows, or landslides. Glacier lake outburst floods might be a major hazard linked to global warming in intensively glaciated mountain ranges, but since they do not appear to be a relevant threat in the Austrian Alps at the moment, we do not discuss them here in further detail. The same applies to ice avalanches (Lieb 2007). However, in the Western Alps the situation may be different (eg Fischer et al 2006). In this article we focus on changes in the occurrence of natural hazards due to glacier retreat or permafrost degradation; these seem to be the two most important processes in the context of global warming and mountaineering.

Changes due to glacier retreat: Since the last glacial maximum in the mid-19th century, a dramatic decrease of the glaciated areas has been observed throughout the Alpine arc (WGMS 2008). Large parts of the now-uncovered areas in glacier forefields consist of debris. Depending on the inclination of the slope, this unstable material provides new potential starting zones for different kinds of mass movements such as debris flows, landslides, or rockfall. Slopes and lateral moraines that have been oversteepened by glacial erosion and have now lost their lateral support due to glacier retreat are particularly susceptible to such processes (Ballantyne 2002; Chiarle et al 2007).

Crucial changes also occur along the upper margins of glaciers. Continuous mass loss causes glacier surfaces to gradually subside. This often reveals heavily jointed and unstable rocks, leading to a high potential for rockfall or continuously falling stones. In the context of mountaineering, this phenomenon mainly affects formerly glaciated passes or ridges leading to summits above glaciers. Many of these routes have become extremely dangerous. Numerous classical ice climbs in the Eastern Alps have become heavily affected by rockfall and falling stones as well due to rocks melting

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TABLE 1 Differences between single events and quasi-continuous events in terms of their relevance to mountaineering.

Type of event	Frequency	Scale of event	Relevance for mountaineering	Examples
Single events	Low	Small to large	Mainly damage and destruction of trail infrastructure	Rockfall, landslide, debris flow
Quasi-continuous events	High to quasi-continuous	Small	Mainly threat to mountaineers	Falling stones from rock slopes, moraines, or glaciers

out at the ice margins (Schwörer 1999), in particular during late summer and autumn. This phenomenon occurs not only on glaciers but also at the margins of steep perennial snowfields, which are quite common along high Alpine trails. It therefore poses a considerable risk to hikers.

A phenomenon specific to steep glacier slopes is the continuous falling of stones previously frozen onto the glacier surface that are released by the daily warming. Global warming leads to an increase both in the occurrence of bare ice and in debris cover, thus additionally increasing the potential for continuously falling stones.

Changes due to permafrost degradation: Permafrost is defined as soil or rock in the ground that remains at a temperature of <0°C for at least 2 consecutive years (Washburn 1973). According to this definition, permafrost may or may not contain ice. In the Eastern Alps, discontinuous permafrost can be found at altitudes above 2500–2900 m, depending on various factors such as aspect and surface material. Since permafrost is not directly visible at the surface, its changes are not obvious and are difficult to detect.

Permafrost reacts very slowly to climatic changes. In most sites complete thawing will only occur after continuous warming over decades or even centuries. However, even partial warming may affect slope stability. The extent of such an impact depends on the ice content of the permafrost, as the cohesion in ice-filled joints decreases with rising temperature (Davies et al 2001). Partial warming of permafrost may be induced by extreme seasonal conditions, as observed during the heat wave in the summer of 2003, when rockfall activity increased noticeably. Most rockfalls occurred near the rock surface and at the lower limit of permafrost distribution, which indicates that the warming of the outer permafrost layer played a major role (Gruber et al 2004). Another effect of permafrost warming is deeper infiltration of meltwater into joints and discontinuities. The associated frost weathering then contributes to the destabilization of rocks (Haeberli and Beniston 1998).

Debris in permafrost areas is often ice-bound. When the active layer of the permafrost melts, the debris loses its cohesion. This process can free large quantities of unstable material in zones with degrading permafrost. Similar to glacier retreat, this results in new potential starting zones for mass movements, mainly debris flows (Hirschmugl 2003).

Relevance to mountaineering: We can summarize that both glacier retreat and permafrost degradation provide additional rock material for different kinds of mass movement processes. Therefore, the potential for fast mass movement events to occur in the affected areas is generally increasing. Yet it always depends on geological factors (eg type of rock, jointing, strike, and dip) and geomorphological factors (eg slope, landform elements) whether the occurrence of these events in a certain area actually increases or not.

Furthermore, a distinction has to be made between the hazard, that is, the potential for an event to occur, and the triggering of the actual event: While the described processes related to global warming might increase the potential, events are generally triggered by other processes that are less linked to global warming, such as extreme rain events.

It must not be overlooked that both glacier retreat and permafrost degradation can also reduce morphodynamics locally, thereby decreasing the occurrence of natural hazards (Lieb 2007). Hence, it cannot be generally stated that the mountains are becoming more dangerous throughout. There is still little known about the frequency of the mentioned hazard events, and to date there are no time series available to prove that these events have become more frequent in the long run (Lieb et al 2007).

From a mountaineer's point of view, it does not really matter which type of mass movement is causing a threat. Far more decisive is the frequency and the scale of the potential hazard event. Regarding relevance to mountaineering, therefore, we suggest looking first at the frequency of events before distinguishing the detailed types of mass movement process, as in practice many events are coincidences of different types of mass movement (see Table 1). Our findings indicate that mountaineers are threatened primarily by small "quasi-continuous events" (Lieb 2007), mainly stones falling from rock walls or glacier slopes.

Changes in the accessibility of the terrain

Introductory considerations: We use "accessibility of the terrain" to refer to the sum of technical difficulties and potential risks associated with moving through the

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FIGURE 1 Terrain sketch illustrating possible locations of the phenomena discussed. The color codes for the different locations correspond to those used in Figure 5. (Figure by Florian Ritter, based on Redaktion Schweizer Lexikon and Gletscherkommission der Schweizerischen Akademie der Naturwissenschaften 1993, p 26)

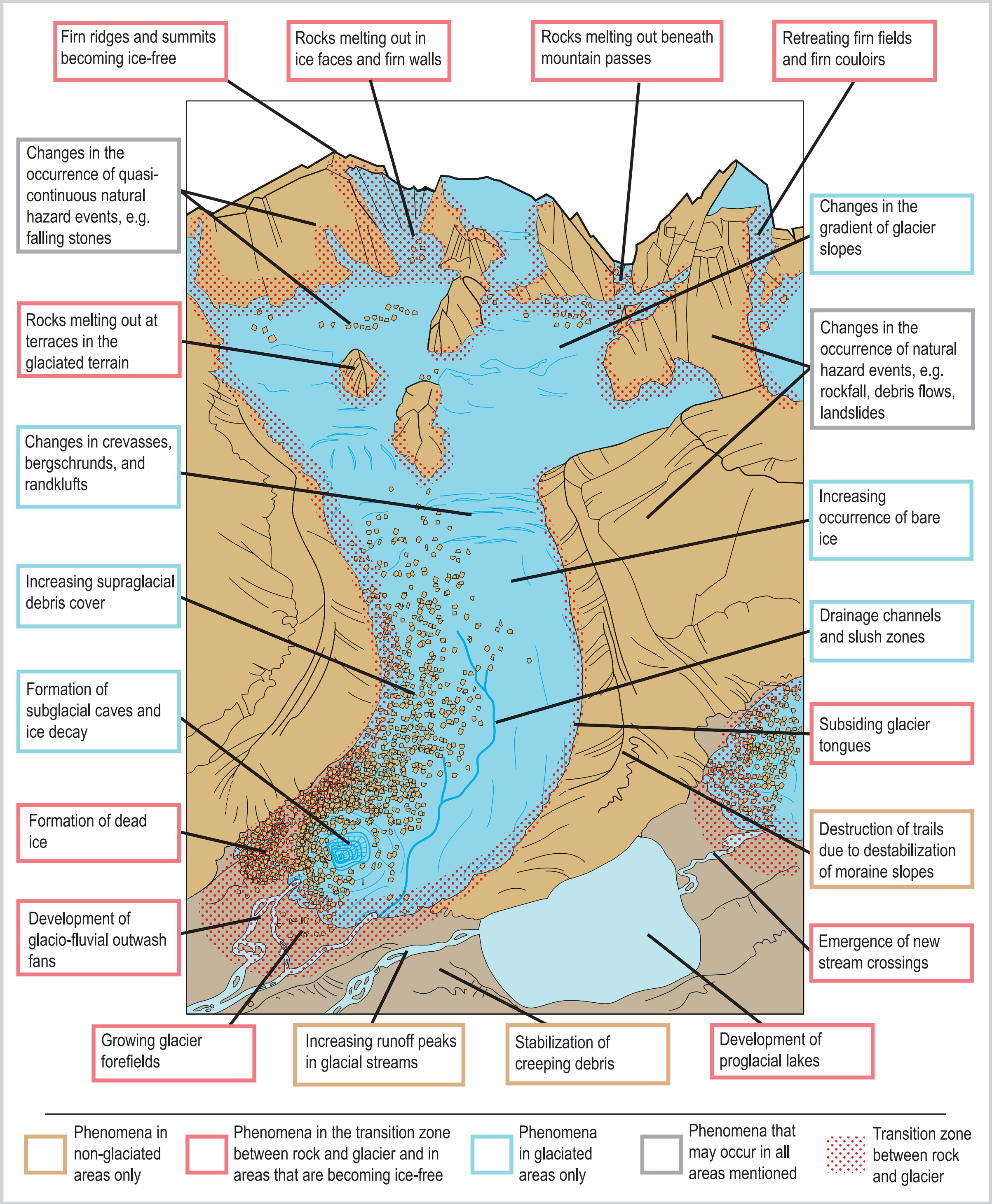

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TABLE 2 Changes in already ice-free areas (see also Figure 2).

Phenomenon	Cause	Effects along trails and routes
Increasing runoff peaks in glacial streams	More frequent heat waves cause extreme runoff peaks in glacial streams, particularly in the afternoon. Bare ice absorbs much more solar radiation than snow, thus causing an additional increase in melting.	Crossings of glacial streams become sometimes impassable, small bridges along hiking trails may be damaged or destroyed. If a heat wave overlaps with heavy precipitation, this may cause dangerous accumulated runoff peaks. As a consequence, it may become necessary to construct new bridges at stream crossings or replace small bridges with larger ones.
		In the long run, runoff peaks will decrease due to a decrease in glaciated area (Figure 2A).
Destruction of trails due to destabilization of moraine slopes	The retreat of glacier tongues at the footslope of steep lateral moraines may destabilize the slope, intensifying erosion and denudation processes.	Trails running above or at the ridge of a moraine (mostly moraines from the 1850s) may be damaged or destroyed by erosion and denudation processes (Figure 2B).
Stabilization of creeping debris	Permafrost degradation in less inclined terrain may stabilize creeping debris due to its consolidation.	The consolidation of creeping debris may eventually reduce maintenance needs for trails in affected areas.

terrain. The effects described in this section may be less important for society as a whole, because they do not threaten settlement areas the way natural hazards might. However, they can be crucial for summer mountain tourism in many Alpine regions.

In our classification we differentiate between hazards and accessibility, as not all changes in the technical difficulty of accessing terrain can be referred to as hazards. For example, a torrential glacial stream that has to be crossed may increase the difficulty of a route or constitute an obstacle, but it is not per se a hazard. When dealing with the consequences of global warming for high Alpine trails and routes, it is thus insufficient to speak exclusively of hazards. We use the term "accessibility" to describe changes that affect trails and routes but do not constitute hazards.

Particular weather conditions and seasonal variation may affect the accessibility of the terrain to a much greater degree than changes related to global warming (Lieb 2007). Most of the phenomena described below are not new in the high Alps, but their intensity, frequency, and spatial distribution may be undergoing significant change. Regarding the temporal scale, we distinguish two types of phenomena:

- Phenomena that follow a continuous trend and are usually linked to processes progressing steadily due to long-term warming, such as glacier retreat and permafrost degradation.
- Phenomena with a high seasonal variation that depend on immediate weather conditions, such as snow cover or meltwater runoff. Both the intensity and the temporal occurrence of this group of phenomena will change due to global warming.

In our classification we characterized about 20 such phenomena that substantially affect the accessibility of trails and routes. We grouped them according to their occurrence along the sections of a mountain tour:

- Changes in already ice-free areas;
- Changes in glacier forefields;
- Changes at the surface of glaciers;
- Changes in summit areas.

The following paragraphs outline the most important characteristics of the phenomena in each section, while Tables 2 to 5 list all phenomena and explain their causes as well as their effects along trails and routes. Figure 1 illustrates possible locations of the phenomena discussed. Of course, the occurrence of natural hazards may change as well in association with the described phenomena. These changes are not mentioned here, as they have been addressed in the preceding sections.

Again, the focus is on phenomena directly and indirectly connected to glacier retreat and permafrost degradation. Other relevant processes could include, for example, increasing erosion problems along hiking trails due to a growing frequency of heavy precipitation events, as claimed by the Alpine Clubs (eg Witty 2007). However, up to now a significant increase of heavy precipitation events in the Alps in summer could not be verified (Schmidli and Frei 2005).

Changes in already ice-free areas: Compared to the possible changes on glaciers and within their perimeter, the changes in already ice-free areas are minor (Table 2; Figure 2). Trails can be damaged or blocked due to erosion processes induced by glacier retreat or excessive runoff peaks of glacial streams. However, terrain can also be stabilized as a result of glacier retreat or permafrost degradation.

Nonetheless, these phenomena show that the accessibility of trails can be impacted even at a great

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FIGURE 2 Examples of changes along trails in already ice-free areas (see also Table 2). (A) Extreme runoff peak in a glacial stream flooding a bridge in the Ötztaler Alpen; (B) partial destruction of a trail along the ridge of the 1850 moraine of a glacier in the Venedigergruppe. (Photos by Erich Heucke and Florian Ritter)

distance from glaciers. This means that such changes affect not only mountaineers heading towards glaciated mountain areas but also hikers using trails that were previously perceived as "safe."

Changes in glacier forefields: Glacier forefields and lateral access routes to glaciers are changing rapidly due to glacier retreat. Whether or not this leads to difficulties in accessing the glacier mainly depends on the type of terrain melting out and on the possibility to build new trail infrastructure.

Growing glacier forefields are often unsuitable for new trail infrastructure due to unstable underground (eg dead ice, unconsolidated debris). In many cases the best route to access the glacier changes from year to year. The Alpine Clubs do not have always the capacities necessary to react to frequently changing conditions. Lakes developing in glacier forefields may require special solutions concerning the trail network (Table 3; Figure 3).

Changes at the surface of glaciers: The accessibility of glaciers changes according to daily and seasonal patterns, as well as from year to year. Global warming will lead to an increase in the occurrence of phenomena that are typical for hot days or summers (eg intense meltwater runoff at the surface, occurrence of bare ice). Phenomena that have not been observed in the Alps for a long time, such as ice decay, may occur.

Since there is usually no trail infrastructure on glaciers, these changes only affect routes without a fixed course. Locally, the accessibility of glaciers can either improve or worsen, depending on the characteristics of the glacier and the prevailing conditions (Table 4).

Changes in summit areas: In many popular routes the transition between the upper margin of a glacier and the rocks of the summit area has become the crux of the whole route. There are many prominent cases where it used to be possible to simply ascend to the summit area by way of a snowy slope or couloir, whereas today these sites have become both dangerous (see "Changes due to glacier retreat" above) and technically very difficult. In many cases it has been necessary to install fixed ropes or other devices such as ladders; however, this is possible only if the rocks revealed from underneath the melting ice are stable. Where rocks are unstable, the route may have to be redesigned completely.

Many classical ice climbing tours throughout the Alps have already either become impassable due to instable rocks melting out or turned into difficult rock climbs (Table 5; Figure 4).

Discussion

Applicability

It was our objective to develop a classification of phenomena related to global warming that affect mountaineering in high Alpine areas. The practical applicability has been successfully tested in three ranges of the Austrian Alps, where a mapping of these phenomena along the high Alpine trail network was conducted (Braun 2009).

In order to develop suitable solutions for the management of trails, different perspectives as well as different kinds of knowledge need to be integrated. Various groups of stakeholders and scientists have to work together in a transdisciplinary way. As an example, we applied the classification in several workshops with local actors and stakeholders to explore the probable future development of the trail network in particular Austrian mountain ranges. Using the classification, we discussed where the various phenomena might occur along the examined trail network over the next decades. Based on this discussion, the stakeholders then sketched different adaptation scenarios. We received very positive feedback regarding the intelligibility and practicability of

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TABLE 3 Changes due to terrain melting out in glacier forefields (see also Figure 3).

Phenomenon	Cause	Effects along trails and routes
Growing glacier forefields	The continuous retreat of glacier fronts leaves vast areas between the maximum glacial extent of 1850 and the current glacier margins ice-free. At present, most glacier fronts in the Austrian Alps shrink by several meters to decameters each year.	Access routes to glaciers are growing longer, with increasing sections leading across debris. Steep terrain may be problematic to traverse due to unconsolidated material or steep rocks polished by the glacier. Construction of new trails in unconsolidated material is often very problematic (Figure 3A).
Emergence of new stream crossings	The retreat of glacier fronts may expose crossings of glacial streams that were previously covered by ice and thus irrelevant for a route. Spatial shifts of the main glacier runoff at the glacier snout can lead to additional stream crossings.	Depending on their size, glacial streams crossing the route can pose serious obstacles to mountaineers. In extreme cases, a route may become impassable. Some cases require the construction of new bridges or relocation of the access route.
Development of glacio-fluvial outwash fans	Glacio-fluvial outwash fans are mainly fine-grained sedimentary depositions in flat glacier forefields. Glacial drainage channels typically branch out into an outwash fan, inducing sedimentation of fine-grained material.	Provided that glacial streams are small enough to cross, outwash fans are easy to traverse if the sediments are consolidated. If meltwater is retained under the surface, however, the fine-grained sediments often form an instable, mud-like ground that is difficult to access and may pose a serious obstacle (Figure 3B).
Development of proglacial lakes	Due to the damming of meltwater runoff by moraine walls, depressions in glaciers may be filled with meltwater once the glacier has retreated, thus forming proglacial lakes.	The development of a glacial lake along a route that originally crossed the glacier may require a detour, but it can also block a valley completely. On the other hand, proglacial lakes can form attractive destinations for hikers.
Formation of dead ice	Ice bodies that have been separated from the rest of the glacier due to its retreat or as a result of ice decay are called dead ice. Usually dead ice is covered with debris.	Dead-ice formations are very unstable and dangerous terrain due to gradual melting and development of hollows under the surface (Figure 3C). Depending on the slope and the relief, they can be difficult and exhausting to cross. The construction of trails in this terrain is virtually impossible.
Subsiding glacier tongues	At present, the surface of most glacier tongues in the Austrian Alps subsides by several meters each year, revealing mainly steep terrain (moraine slopes, polished rocks) at the lateral glacier margins.	Depending on the steepness of the terrain and the emerging material, access routes to glaciers may become more difficult or even impossible to pass. The terrain itself may pose a risk of falling to mountaineers.

FIGURE 3 Examples of changes due to terrain becoming ice-free in glacier forefields (see also Table 3). (A) Unconsolidated debris slope along a route in a glacier forefield in Silvretta; (B) glacio-fluvial outwash fan developing below a glacier in the Ötztaler Alpen; (C) melted hollow in an intensely debris-covered patch of dead ice in the Ötztaler Alpen. (Photos by Florian Ritter)

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TABLE 4 Changes at the surface of glaciers.

Phenomenon	Cause	Effects along trails and routes
Drainage channels and slush zones	Due to increased melting, drainage channels at the glacier surface may show high runoff peaks in the afternoon. Slush zones are a mixture of water, snow, and ice resulting from stagnant meltwater in flat glacial terrain; their formation can be increased or reduced by melting processes.	Drainage channels may pose a considerable linear obstacle to mountaineers, especially in the afternoon. If impassable, they can force mountaineers into detours (even below the glacier: see "Increased runoff peaks" in Table 2). Depending on their depth, slush zones are merely exhausting terrain or pose an obstacle that requires an extended detour.
Formation of subglacial caves and ice decay	Long-lasting mass loss of glaciers leads to reduced ice movement. This can result in the formation of subglacial caves and hollows, mainly near the margins and the front. Dissolution of ice over larger areas is called ice decay and often results in vast masses of dead ice.	Subglacial hollows pose a risk of falling to mountaineers. This is particularly true for debris-covered glaciers, as in such cases hollows are often invisible and most mountaineers do not expect a risk of falling in this terrain. Decaying glaciers are a rapidly changing, confusing terrain and should therefore be avoided by mountaineers.
Changes in crevasses, bergschrunds, and randklufts	Reduced ice movement results in fewer crevasses overall. At the same time, reduced snow cover leads to thinner snow bridges across crevasses and more open crevasses. This also applies to randklufts (= gap between rock and ice at the margin of a glacier) and bergschrunds (= large topmost crevasse of a glacier).	Thinner snow bridges increase the risk of falling into a crevasse, whereas the visibility of crevasses in entirely bare ice reduces the risk of falling. The increasing number of open crevasses means more obstacles to mountaineers. Especially the crossing of randklufts and bergschrunds at the margins of glaciers poses increasingly severe problems. At the same time, the overall reduction in crevasses reduces the number of potential obstacles. Locally, the situation for mountaineers can both improve and worsen.
Increasing occurrence of bare ice	Bare ice is increasingly exposed due to the general decrease in snow cover.	Bare ice on flat sections is easy to cross. However, the technical difficulties associated with steep glacier slopes (eg routes leading to mountain passes) and ice climbs increase considerably, as does the risk of falling.
Increasing supraglacial debris cover	Glacier retreat and permafrost degradation increase the potential of mass movements depositing material on the glacier surface. As a result, supraglacial debris covers are generally growing. In addition, high melt-off rates result in more stones from inside the ice melting out onto the surface.	The consequences for mountaineering are similar to those of debris-covered dead ice (see "Formation of dead ice" in Table 3). The accessibility of a debris-covered glacier depends on the gradient, the thickness of the debris cover, and the type of debris. Flat debris-covered glaciers are generally less difficult to cross than steep ones.
Changes in the gradient of glacier slopes	The gradient of glaciers may either increase or decrease due to mass loss: Where surface bulges decline (eg at glacier tongues), the gradient decreases. Conversely, the gradient of concave glacier slopes (eg at the upper end of a cirque) may increase.	Accessing flattened glacier tongues may often be easier than before. However, the opposite process seems more relevant to mountaineering: routes leading to glaciated mountain passes at the upper ends of cirques are frequently affected by the steepening of slopes, making such passes more difficult to access. For a detailed description of examples, see Braun (2009).

the classification from all participating groups (Ritter et al 2010).

Limitations

Our classification is based on changes concerning natural hazards and accessibility. Such changes can, of course, affect the overall character of an Alpine landscape and the attractiveness of certain tours to mountaineers, with considerable effects on mountain huts and the local economy (Figure 5). However, we did not include these aspects in our classification, as they refer to a different spatial scale.

Generalizability

The classification scheme was developed from data mostly referring to the Eastern Alps, in particular the Austrian Alps. We believe that it can be applied to other parts of the Alps and, with specific adaptations, presumably also

TABLE 5 Changes due to terrain melting out in summit areas (see also Figure 4).

Phenomenon	Cause	Effects along trails and routes
Rocks melting out beneath mountain passes	Glacier retreat causes the upper margins of glaciers subside. As a consequence, rocks melt out beneath glaciated mountain passes. The reduced snow cover in summer accelerates the ongoing exposure of rocks.	The rocks exposed are usually steeper than the former glacier slope. They are often also heavily jointed and unstable and therefore difficult and dangerous to access, in addition to being more prone to natural hazards. In many cases it would be necessary to install fixed ropes to support mountaineers, but in instable terrain this is not always possible. Access routes to mountain passes are very important to mountaineers, because most routes leading to summits or crossing from one valley to another head towards a mountain pass first (Figure 4A).
Retreating firn fields and firn couloirs	The retreat of snow and ice affects not only glaciers, but also firn couloirs and firn fields. As a result, routes gradually melt out, uncovering rocks from below.	The effects on mountaineering are similar to those described above for rocks melting out beneath mountain passes. Firn fields and firn couloirs are also quite common along high Alpine hiking trails, so these changes can affect mountaineers as well as hikers, who may be less well equipped and experienced.
Rocks melting out at terraces in the glaciated terrain	Rocks that were previously covered in ice may melt out at the edges of terraces in the glaciated terrain due to mass loss of the glacier.	Depending on their steepness and stability, the rocks thus exposed can be difficult to access and may even block a glacier route completely.
Firn ridges and summits becoming ice-free	The shape of firn ridges and firn summits changes from year to year depending on seasonal atmospheric conditions. Nevertheless, they tend to disappear in the long run due to global warming, revealing rocks of varying stability.	Routes may become either easier or more difficult when a firn ridge disappears, depending on the type of rocks exposed, the form of the ridge, etc (Figure 4B). Firn summits may decrease in height due to gradual ice loss. Stability problems may arise with summit crosses, and parts of summits may collapse.
Rocks melting out in ice faces and firn walls	Ice faces and firn walls often consist of a fairly thin ice layer. As a result, they are very vulnerable to mass loss induced by global warming. Once rocks are exposed, adjacent rocks rapidly melt out as well.	Many classical ice climbs have turned into mixed climbs (a combination of climbing in ice and rock), mostly associated with increasing difficulties and risks. More importantly, the danger of rockfall increases substantially in most affected ice faces, making many tours less and less accessible from year to year.

to most glaciated mountain ranges outside the Alps. Adaptations might be necessary due to different geological, morphodynamic, and climatic situations, as well as different forms and traditions of mountaineering.

Before applying the classification in other mountain regions, it would be necessary to investigate whether local practitioners, such as mountain guides or trail workers, are familiar with the phenomena it describes. In addition, it would have to be checked whether they are confronted with additional problems that are not considered in the classification. Expert interviews would constitute an appropriate approach to retrieving this information and could help to identify the need for additional field research in the relevant area.

Anticipatory implementation

It is essential with a view to maintaining an attractive trail network in high Alpine areas that problematic morphodynamic developments be recognized before the affected trails or routes become impassable. It should be possible to look for alternatives well ahead of time, for example, by providing different routes. It is therefore crucial to identify and anticipate expected future changes in the terrain linked to global warming.

Our findings suggest that the majority of the phenomena can be found in almost all heavily glaciated mountain areas. Our classification could be used to derive criteria for recognizing these spots. Using Geographic Information Systems (GIS) analysis, the terrain along trails could be checked against these criteria in order to detect critical spots that might become problematic in future.

Conclusions

Hiking and mountaineering have always been performed in terrain characterized by increased occurrence of

FIGURE 4 Examples of changes due to terrain becoming ice-free in summit areas (see also Table 5). (A) A formerly easily accessible firn ridge in the Ötztaler Alpen has turned into an unstable, hazardous rock ridge; (B) an old ascent route to a mountain pass in the Stubaier Alpen leading through a firn couloir (orange) has melted out and been replaced with a newly built route equipped with fixed ropes across compact rock (red). (Photos by Florian Ritter)

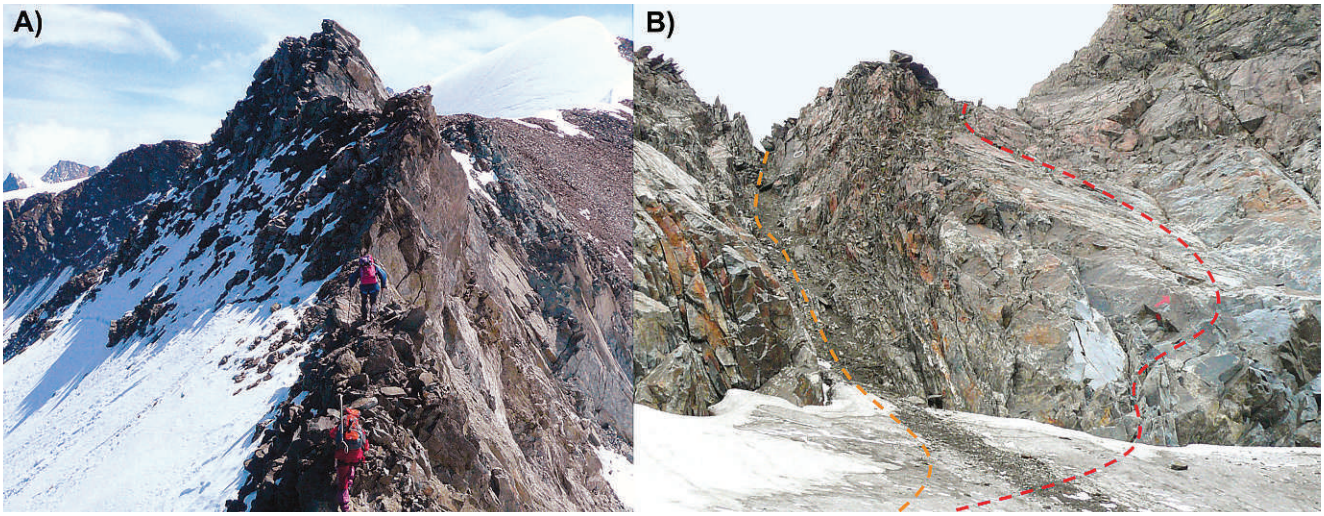
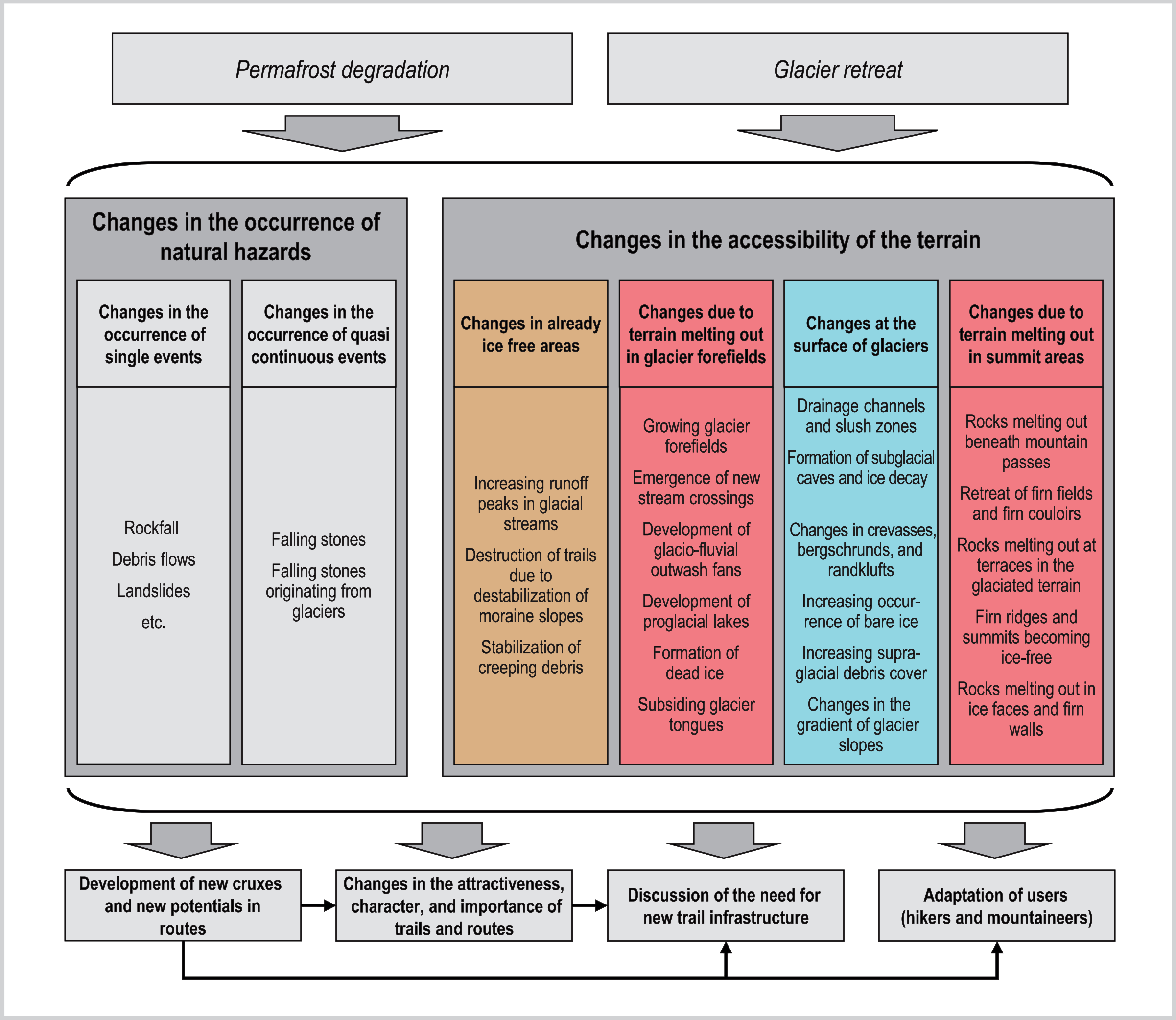


FIGURE 5 Overview of phenomena and the resulting changes affecting the high Alpine route and trail network. The color codes for the different locations of phenomena correspond to those used in Figure 1. (Figure by Florian Ritter)



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natural hazards and low management intensity. It is part of the activity's identity that mountaineers are responsible for their own safety in the Alpine environment. The risk situation along high Alpine trails and routes thus cannot be compared to the situation in residential areas, for example, where natural hazard management has to be much more intensive.

The collected examples show that in the context of global warming numerous different types of phenomena can affect the accessibility of high Alpine trails and routes, in terms of both the occurrence of natural hazards and technical difficulty. Threats and difficulties can increase or decrease depending on the specific situation, but usually a worsening of the situation receives more attention than an improvement.

Extending the legal liability of trail holders and maintenance staff is not a sensible solution. Instead, we recommend addressing the problem awareness of users (hikers, mountaineers) and their personal responsibility. However, they should not be scared away, as it often happens when only disasters are reported in the media. The effects of global warming on the high Alpine terrain are not exclusively negative. From the point of view of infrastructure management it is essential to see new opportunities as well, such as the possibility of developing new ascents in areas that have become ice-free.

In Figure 5 we present a possible framework for investigating effects and developing management measures at the local level. This can be successfully implemented only by involving a wide variety of stakeholders (see Ritter et al 2010). The cumulative effects of numerous individual critical developments at the local level can also induce a need for strategic decisions at a different level, such as a complete redesign of the trail network or even the abandonment of trail maintenance in critical sections of a mountain range.

Planning and management of trail networks have to be adaptive and future oriented. Trail holders have to look for alternatives ahead of time. Our findings show that many problems are foreseeable. Action should be taken before severe accidents happen or trails become completely impassable. We hope that our classification can serve to support the development of integrative adaptation strategies.

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REFERENCES

Ballantyne CK. 2002. Paraglacial geomorphology. *Quaternary Science Reviews* 21:1935–2017.

Braun F. 2009. Sommer-Bergtourismus im Klimawandel: Szenarien und Handlungsbedarf am Beispiel des hochalpinen Wegenetzes [PhD dissertation]. Vienna, Austria: University of Natural Resources and Life Sciences.

Chiarle M, Iannotti S, Mortara G, Deline P. 2007. Recent debris flow occurrences associated with glaciers in the Alps. *Global and Planetary Change* 56(1–2):123–136.

Davies MCR, Hamza O, Harris C. 2001. The effect of rise in mean annual temperature on the stability of rock slopes containing ice-filled discontinuities. *Permafrost and Periglacial Processes* 12:137–144.

Fischer L, Kääb A, Huggel C, Noetzli J. 2006. Geology, glacier retreat and permafrost degradation as controlling factors of slope instabilities in a high-mountain rock wall: The Monte Rosa east face. *Natural Hazards and Earth System Sciences* 6:761–772.

Gruber S, Hoelzle M, Haeberli W. 2004. Permafrost thaw and destabilization of Alpine rock walls in the hot summer of 2003. *Geophysical Research Letters* 31(13).

Haeberli W. 1999. *Eisschwund und Naturkatastrophen im Hochgebirge*. Zurich, Switzerland: vdf.

Haeberli W, Alean J, Muller P, Funk M. 1989. Assessing risks from glacier hazards in high mountain regions: Some experiences in the Swiss Alps. *Annals of Glaciology* 13:96–102.

Haeberli W, Beniston M. 1998. Climate change and its impacts on glaciers and permafrost in the Alps. *Ambio* 27(4):258–265.

Harris C, Davies MCR, Etzelmüller B. 2001. The assessment of potential geotechnical hazards associated with mountain permafrost in a warming global climate. *Permafrost and Periglacial Processes* 12(1): 145–156.

Hirschmug M. 2003. Debris flows in the mountain permafrost zone: Hohe Tauern national park (Austria). *In:* Phillips M, editor. *Proceedings of the Eighth International Conference on Permafrost, 21–25 July 2003, Zurich, Switzerland*. Lisse, The Netherlands: Balkema, pp 413–418.

Kapelari P. 2008. Der Weg ist das Ziel. Das Wegenetz des Alpenvereins ist keine Selbstverständlichkeit. *Bergauf* 04(2008):6–9.

Lieb GK. 2007. Vom Klimawandel beeinflusste Naturprozesse im Hochgebirge als potenzielle Gefahren für Freizeitaktivitäten. *In:* Wohlschlägl H, editor. *Beiträge zur Humangeographie und Entwicklungsforschung. Geographischer Jahresbericht aus Österreich*. Vienna, Austria: Institut für Geographie und Regionalforschung, pp 79–94.

Lieb GK, Kellerer-Pirklbauer A, Avian M. 2007. A preliminary map of geomorphological hazards caused by climate change in the Großglockner Mountains (Austria). *In:* Kellerer-Pirklbauer A, Keiler M, Embleton-Hamann C, editors. *Geomorphology for the Future*. Innsbruck, Austria: Innsbruck University Press, pp 137–144.

Muhar A, Schauppenlehner T, Brandenburg C, Arnberger A. 2006. Alpine summer tourism: the mountaineers' perspective and consequences for tourism strategies in Austria. *Forest, Snow and Landscape Research* 81(1/2): 7–17.

Nötzli J, Gruber S, Hoelzle M. 2004. Permafrost und Felsstürze im Hitzesommer 2003. *GEOforum actuel* 20:11–14.

Redaktion Schweizer Lexikon und Gletscherkommission der Schweizerischen Akademie der Naturwissenschaften, editors. 1993. *Gletscher, Schnee und Eis: Das Lexikon zu Glaziologie, Schnee- und Lawinenforschung der Schweiz*. Visp, Switzerland: Verlag Schweizer Lexikon, Mengis und Zier.

Ritter F, Muhar A, Fiebig M. 2010. Transdisziplinärer Dialog: Fachwissen und Erfahrungswissen im Austausch über Sommer-Bergtourismus und Klimawandel. *GAIA* 19(3):194–203.

Rosenthal G. 2008. *Interpretative Sozialforschung: Eine Einführung*. Weinheim, Germany: Juventa.

Schmidli J, Frei C. 2005. Trends of heavy precipitation and wet and dry spells in Switzerland during the 20th century. *International Journal of Climatology* 25(6):753–771.
Schwörer D. 1999. Klima und Alpinismus im Wandel der Zeit. Available at: http://www.alpineresearch.ch/1/; accessed on 10 September 2010.
Washburn AL. 1973. *Periglacial processes and environments*. London, United Kingdom: Arnold.
WGMS [World Glacier Monitoring Service]. 2008. *Global glacier changes: facts and figures*. Zurich, Switzerland: World Glacier Monitoring Service.
Witty S. 2007. "New Tool" – Neues Werkzeug – GIS. *In:* Oesterreichischer Alpenverein Fachabteilung Raumplanung-Naturschutz, editor: *Die Arbeitsgebiete der Alpenvereine zwischen Rückzug und neuen Ufern*. Innsbruck, Austria: Alpine Raumordnung, pp 61–65.

http://dx.doi.org/10.1659/MRD-JOURNAL-D-11-00036.1