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AUTHOR'S NOTE

Acknowledgments

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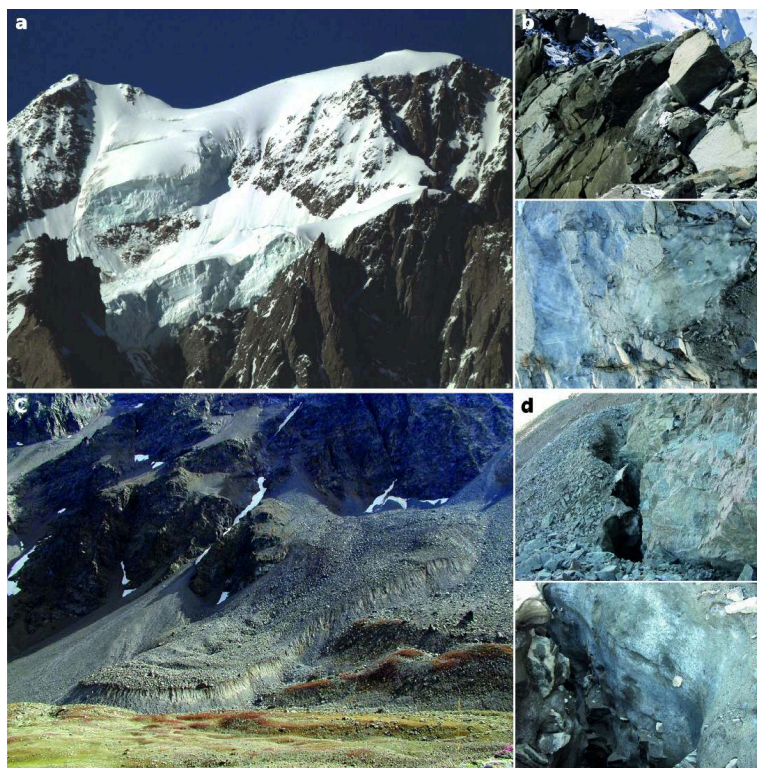
Introduction

- 1 Permafrost is a major element of the mountain cryosphere (Gruber and Haeberli, 2009): recognising and understanding its response to global warming is an important scientific and societal issue. Permafrost warming on mountain slopes can have

damaging consequences for Alpine territories, especially in terms of risk. For example, the destabilisation of rock slopes or surficial deposits because of: 1) the rising temperature of ground ice, 2) the modification of the ice content or 3) the disappearance of ice, can trigger fast and complex hydro-geomorphological processes, notably due to the effect of the relief.

- 2 Two types of environment are particularly examined: 1) high-altitude rock walls, which are very sensitive to short-term climate evolution, due to their direct contact with the atmosphere and limited ice content, and 2) surficial deposits in which the climate signal is regulated by the seasonal presence of a thermally buffering snowpack and high ice content. The visible markers of these two types of permafrost are hanging glaciers on rock walls because their cold base is fixed on the permafrost-affected bedrock (Gruber and Haeberli, 2007; Fig. 1a) and rock glaciers – mixtures of ice and rock debris affected by a slow and steady creep (Haeberli *et al.*, 2006; Fig. 1c) – respectively. Permafrost ice can be seen on rare occasions in rock wall fractures or rockfall scars (Fig. 1b) and in open tension cracks in rock glaciers (Fig. 1d).

Figure 1. Main evidence for permafrost presence in mountain environments

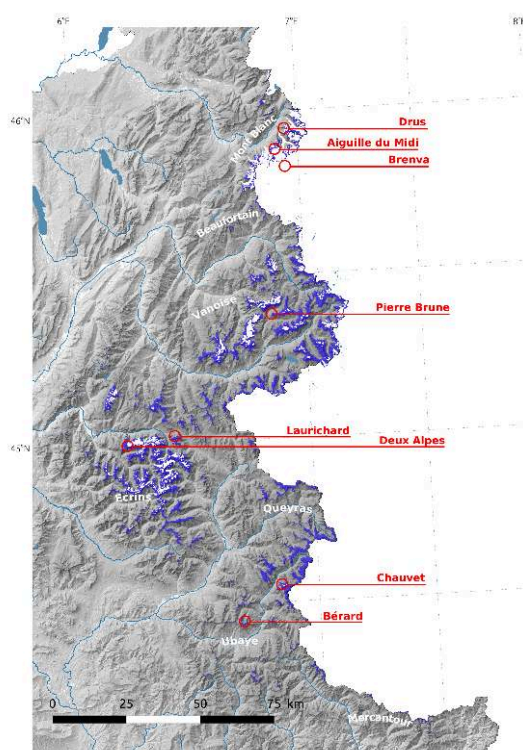


a) Hanging glacier on the south summit of the Grandes Jorasses, whose front reaches 3980 m asl. (Mont Blanc massif); b) ice visible in scarps in the Arête des Cosmiques, at 3605 m asl. In 2006 (upper image) and on the west face of the Petit Dru, 3530 m asl. In 2011 (lower image, width of the photo: ~ 50 cm) in the Mont Blanc massif; c) Laurichard rock glacier, whose front reaches 2420 m asl. (Combeynot massif; photo by E. Thibert, 2004); d) Rooting zone of the Laurichard rock glacier, with the temporary "rimaye" visible in 2003 (upper image) and the ice visible inside the same rimaye (lower image, width of the image ~ 1 m).

- 3 In France, initial studies recognising the presence of permafrost and its role in alpine environments date from the early 1980s (Francou, 1981; Evin, 1983). The year 2003 saw a renewed interest in this subject (theses of Monnier in 2006, Bodin in 2007, Ravanel in 2010, Echelard and Perrier in 2014, and Magnin in 2015). The probable extent of

permafrost in the French Alps is estimated by authors at between 700 and 1500 km² (Fig. 2) *i.e.* 10 to 20 % of the area above 2000 m asl. (Boeckli *et al.*, 2012; Bodin *et al.*, 2008; Magnin *et al.*, 2015a). Since 2005, significant efforts have been made to study both the thermal state of permafrost, which reflects past and current climates in high mountain areas, and the associated geomorphological dynamics. Instrumented boreholes, subsurface thermal measurements, and monitoring of morphodynamics are used to characterise the status of the permafrost in rock walls (Magnin *et al.*, 2015b) or in surficial deposits (Bodin *et al.*, 2009; Schoeneich *et al.*, 2014) in the French Alps and its response to ongoing climate change. Most of this research is part of the French observation and permafrost monitoring network PermaFRANCE (Schoeneich *et al.*, 2010). The study sites are located between 44 and 46°N, and between 2400 and 4500 m asl. (Fig. 2).

Figure 2. Potential distribution of permafrost in the French Alps (after Bodin *et al.*, 2008) and location of the main sites referred to in this paper



- 4 The aim of this work is to provide an overview of the key knowledge on permafrost in the French Alps. It presents: 1) available thermal measurements, both at depth – *i.e.* in the permafrost itself – and near the surface and 2) the main results of the studies on geomorphological dynamics associated with the presence of mountain permafrost. The joint evolution of the thermal state of the permafrost and climate is compared to the evolution of phenomena such as rockfalls in the Mont Blanc massif or the flow velocity of the Laurichard rock glacier in the Ecrins massif. Finally, future prospects in terms of hazards and possible emerging risks are discussed.

Current permafrost temperatures and trends

Measurement in boreholes

- 5 Measuring the thermal regime of the subsurface below the active layer – which freezes and thaws seasonally – is the only way to characterise the state of the permafrost. For this purpose, boreholes equipped with continuously measuring temperature sensors have been operating since 2009 in three different geological and geomorphological contexts.

The 2Alpes-3065 deep vertical borehole

- 6 A 100-m-deep borehole was drilled in 2010 at 3065 m asl., close to the Deux Alpes ski resort (Fig. 2). The borehole was set up on a wide and homogeneous gneissic dome, in order to characterise the long-term evolution of the thermal profile of the bedrock. It is equipped with both a sensor chain (30 PT100 thermometers from 0 to 98 m in depth) and an optical fibre for measuring the distributed temperature (Schoeneich *et al.*, 2012). The four years of available data (December 2010 - July 2014) show a 4.5- to 5.5-m-deep active layer, a seasonal penetration up to 25-30 m, a stable temperature (-1.3°C) at 30 m in depth, and -0.7°C at the base of the borehole. The permafrost here is therefore more than 100-m-deep. An extrapolation of the geothermal gradient suggests that the permafrost base is around 180 m in depth.

Boreholes in the Aiguille du Midi rock walls

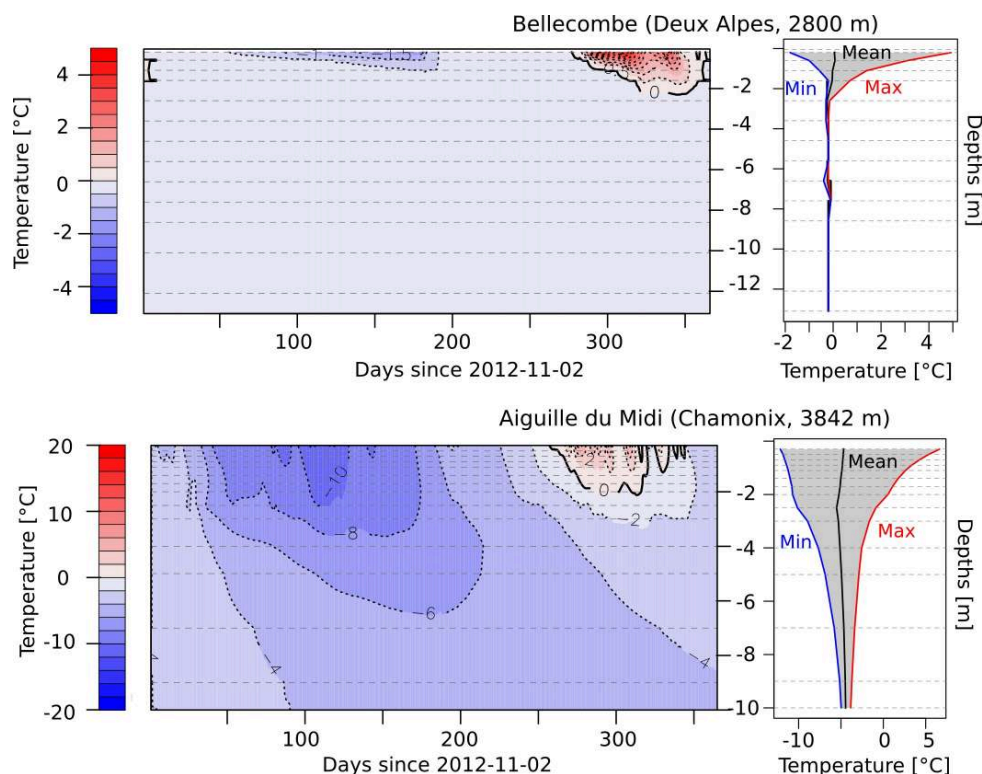
- 7 The summit of the Aiguille du Midi is composed of a set of three granite peaks culminating at 3842 m asl. (Fig. 2). It can be reached from Chamonix by cable car. In September 2009, three 11-m-deep horizontal boreholes were drilled in the S (3753 m asl.), NW (3738 m) and NE (3745 m) faces of the Central Piton. Each of them was equipped with a chain of 15 thermistors (accuracy $\pm 0.1^{\circ}\text{C}$) measuring temperature between 30 cm and 10 m in depth every 3 h (Magnin *et al.*, 2015b). The mean annual temperatures at 10 m indicated a warm permafrost in the S face (-1.5°C) and a cold one in the NW (-4.5°C , Fig. 3) and NE (-3.6°C) faces. The thermal gradient is positive in the NW borehole and negative in the S one, certainly because of the lateral heat flow from the sunny to the shady side. The thickness of the active layers is on average between 2.2 m (NW) and 5.7 m (S), with different inter-annual variations in thickness from one borehole to another.

Boreholes in the Bellecombe rock glacier

- 8 Two 15-m-deep boreholes were drilled in 2009 in the Bellecombe rock glacier (2700-2750 m asl.) in the Deux Alpes ski area (Fig. 2). They crossed a 2.5-m-deep active layer of coarse debris, then an ice-rich or even massive ice layer up to 9.5 m in depth, before reaching bedrock. Each of them is equipped with 15 sensors (PT100) installed between 0 and 13.5 m in depth.
- 9 The five years of available data (October 2009 - October 2014) show an isothermal and warm permafrost; -0.1 to -0.2°C throughout the profile and throughout the year below a ~ 2.5 -m-thick active layer (Fig. 3). Seasonal variations in ground temperature are

limited to the active layer and are blocked by the ice-rich permafrost table below, which is very close to the melting point.

Figure 3. Thermal regime during one year for two types of permafrost, measured in the Bellecombe rock glacier and in the NW rock face of the Aiguille du Midi



On the left, the daily ground temperatures interpolated with depth (grey dashed lines indicate the depth of the sensors) and on the right, the vertical profiles of the minimal, maximal and average values for 2013.

- 10 Comparing the thermal regimes measured in the Bellecombe and Aiguille du Midi boreholes highlights the effect of the presence of a high ice content in rock glaciers: the melting of this ice absorbs the atmospheric heat, limiting its propagation in depth. The permafrost temperature variations are thus greater in rock walls, where the depth of the active layer can thicken for several metres during a hot summer. In contrast, the cooling of ice-rich permafrost at the melting point is slow, due to the required latent heat. These environment-specific features, which largely regulate the geomorphological responses of alpine slopes, can also be combined.

Measurement of the surface temperature

- 11 Because of the limited possibility of equipping boreholes, due to the cost, ground thermal monitoring is completed by temperature measurements continuously carried out by autonomous sensors placed in the rock subsurface (1-5 cm) or in surficial deposits (10-50 cm). For permafrost, the surface temperature can be interpreted as the “thermal signal input” and, in winter, when the snow cover insulates the surface sufficiently from the atmosphere, as an indicator of the thermal conditions at depth.

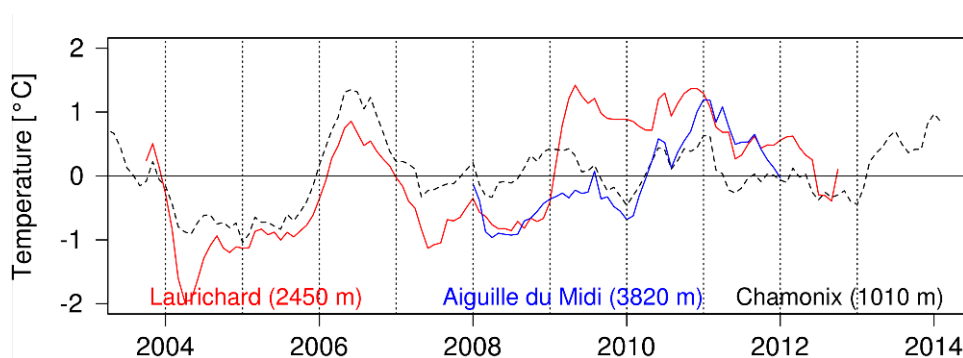
Rock walls

- 12 Since 2005, nine sensors recording the temperature between 3 and 55 cm in depth have been installed in the N, E, S and W faces of the Central Piton of the Aiguille du Midi. Considering the other sensors located at a depth of 30 cm in the boreholes (section 1.1.2), twelve surface sensors are available to measure the temperature distribution. A difference of 8°C has been observed between the N and S faces. The surface offset, *i.e.* the temperature difference between the rock wall surface and air (positive value), mainly resulting from the radiation balance, is 1-2°C in the N face and 9-10°C in the S face. Four of the sensors have been affected by the presence of snow, whose thickness has frequently been over 60 cm for three of them. Two of these, which are located in the S face, have been recording a lower mean annual temperature than that recorded by the sensors without snow but with the same aspect. On the contrary, the other heavily snow-covered sensor located in the N face records warmer conditions than the snow-free sensors with the same aspect. Finally, the sensor covered by less snow has recorded colder conditions than those in shady conditions, which reflects the cooling effect of a thin layer of snow.

Rock glaciers

- 13 In October 2003, seven autonomous temperature sensors were placed at a few tens of centimetres below the surface of the Laurichard rock glacier, sheltered from direct solar radiation (Figs. 1 and 2). The data clearly show the important role of snow in the surface thermal regime, and the variability of the winter thermal regime. As a result, winters with abundant and early snow (as in 2003-2004 and 2006-2007) have led to a clear decoupling between the ground and the atmosphere, which minimises the winter cooling. In contrast, winters with low snow cover, such as 2004-2005, have promoted heat loss from the surface and therefore a cooling at depth.

Figure 4. Evolution of the deviation from the mean (average of the 2003-2012 period) ground subsurface temperature (filtered with a 12-month window) on the Laurichard rock glacier and the Aiguille du Midi east rock face. The deviation from the mean air temperature at the Chamonix weather station (data from Météo France) is also presented



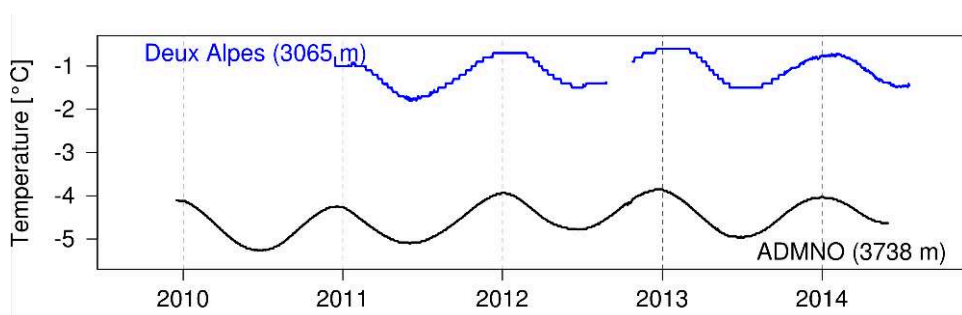
- 14 In order to filter seasonal fluctuations, analyses of the surface temperature were carried out using moving averages (over the previous 12 months), which highlight significant trends (Fig. 4). For the Laurichard rock glacier, two parallel trends were superimposed: inter-annual variability mainly related to snow (but heat waves have also been observed, such as that of autumn 2006) and a relatively continuous rise in temperature over the observed period. The data from the Aiguille du Midi show a closer

coupling with the air temperature, due to the thin snow cover or even its absence on some measurement sites.

Evolution of permafrost temperatures and climate control

- 15 The mid- and long-term evolution measured in the permafrost can be described due to the temperature recorded at several metres in depth, where the seasonal influence is reduced (it is usually annulled at 15-25 m). During the 4 years of available data for the 2Alpes-3065 and the 5 years available for the Aiguille du Midi NW face boreholes, the observable tendency of increasing temperatures reaches 0.04°C per decade for the former and 0.08°C per decade for the latter. This increase is similar to that observed in recent years in the Swiss Murtel borehole (10 years, longest available series in the Alps), which is consistent with the recent data from other Alpine boreholes, where it seems to have started in 2007 (PERMOS, 2013). Moreover, the low thermal gradient observed in the profile probably reflects the warming trend of near-surface layers, in response to the rising temperatures of the last 30 years (Harris *et al.*, 2001).

Figure 5. Evolution of the permafrost temperature (at 10 m of depth for the Aiguille du Midi NW borehole ADMNO, and at 11 m for the 2Alpes-3065 borehole) in flat bedrock (Deux Alpes) and in a vertical rock face (Aiguille du Midi)



Morphodynamic responses to permafrost changes

Typically observed functioning

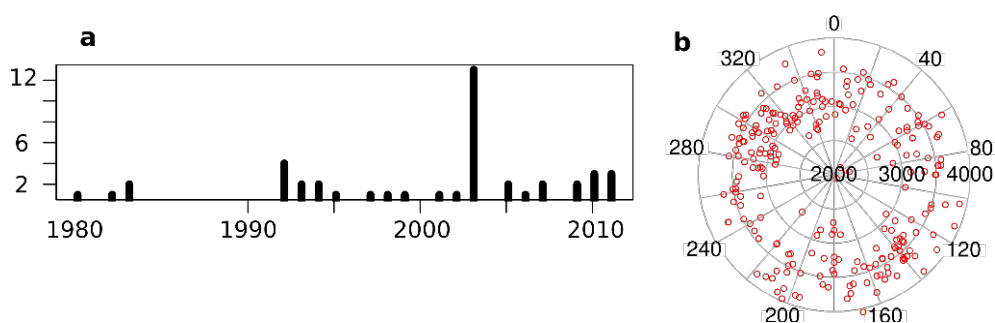
- 16 The evolution of mountain permafrost affects slope dynamics, including block falls, rockfalls and rock avalanches from rock walls, and rock glacier movements in surficial deposits. In order to detect possible changes in processes, their seasonal and inter-annual components in response to climate variability must be known. Only long-term monitoring and historical reconstitutions make it possible to describe “usual” activity.

Rockfall activity in the Mont Blanc massif

- 17 Unlike for rock glaciers whose flow corresponds to an intrinsic dynamic, “normality” for a rock wall is a relative stability on the multi-secular scale (*cf.* Böhlert *et al.*, 2008), favoured in the Mont Blanc massif by a competent rock (granite). As a result, on the N side of the Aiguilles de Chamonix and on the W face of the Drus, almost no collapse was observed between the end of the Little Ice Age (1855 c.) and 1936 (Ravanel and Deline, 2008; Ravanel and Deline, 2011). The low temperatures have probably maintained the stabilising permafrost in the rock walls, while ice/snow cover, widely developed on

many faces (Delaloye 2008), has stabilised them, despite their dense fracturing. However, the stability of high mountain rock walls has sharply deteriorated over the last two decades, as shown by the inventories of rockfalls in the Aiguilles de Chamonix (Fig. 6a). The frequency of rockfalls peaked during the hot summer of 2003, with 182 rockfall deposits on the Mont Blanc glaciers (Ravel *et al.*, 2011). Since 2007, rockfalls have been almost systematically documented in 60 % of the massif (Ravel *et al.*, 2010; Ravel and Deline, 2013). The 350 collapses surveyed from 2007 to 2014 predominantly occurred at altitudes characterised by a warm permafrost (*i.e.* with a temperature between -2 and 0°C according to Magnin *et al.*, accepted; Fig. 6b), and during warm periods. The role of the permafrost in rockfall triggering has been suggested by several other observations: ice or water flow observed in scars; collapses occurring at higher elevation in hot summers; a strong contrast in the elevations of triggers between north and south faces; and pillars, spurs and ridges – with a strong permafrost degradation – being particularly affected by rockfalls (Ravel and Deline, 2015).

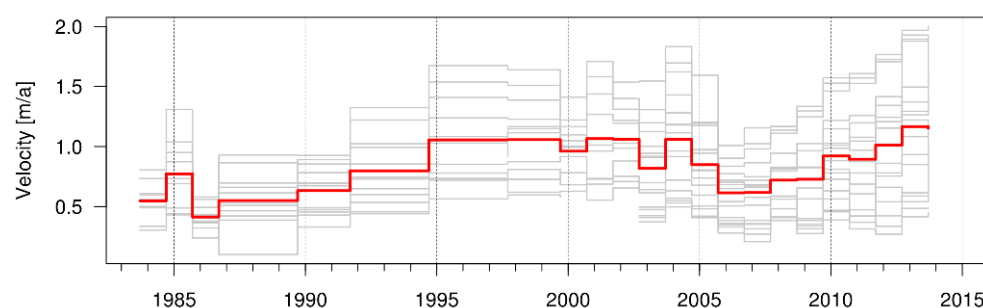
Figure 6. a) Annual number of rockfalls in the Aiguilles de Chamonix since 1980, based on photocomparison; b) Elevation (in metres) and orientation (in $^{\circ}$) of the set of rockfalls inventoried by observers in the Mont Blanc massif between 2007 and 2011



Rock glacier dynamics

- 18 Most of the alpine rock glaciers are flowing with velocities ranging from a few decimetres to 1-2 m per year, with inter-annual and seasonal variations (Haeberli *et al.*, 2006). The movement of the Laurichard rock glacier has been surveyed annually for thirty years (Francou and Reynaud, 1992) by measuring the position of blocks on its surface, carried out since 2000 by the Ecrins National Park.

Figure 7. Mean annual velocity (taken from 25 blocks measured annually by geodetic survey) of the Laurichard rock glacier between 1985 and 2012 (grey curves are the individual surveyed points).



- 19 This data set (Fig. 7) shows a change in velocity that is very similar in its inter-annual variations to that recorded on other alpine rock glaciers (*i.e.* Kääb *et al.*, 2007; Delaloye

et al., 2008). The 1990s were marked by a gradual acceleration with, in the case of Laurichard, two velocity peaks in 2001 and 2004 (Bodin *et al.*, 2009). Then lower velocities were observed until 2008, followed by a further acceleration that is still ongoing (Schoeneich *et al.*, 2014), similar to what has happened elsewhere in Switzerland (PERMOS, 2013) and Austria (Kellerer-Pirklbauer *et al.*, 2012).

- 20 This comparable behaviour throughout the Alps suggests a common climate control. Although the thermal conditions of the Laurichard rock glacier are only indirectly known from the measurements of its surface temperature since 2003, several factors may explain the response of rock glaciers to climate signals (Bodin *et al.*, 2009). On the one hand, the increasing air temperature observed in the 1990s could have warmed the rock glacier, causing greater deformation of the ground ice. On the other hand, winters with thin snow cover could have resulted in a cooling of the ground and a decrease in speed. Finally, given the very low thermal conductivity of permafrost, the impact of liquid water (*e.g.* due to spring melt) on the rock glacier body could explain these velocity variations, as well as the seasonal ones measured at some Swiss sites (Perruchoud and Delaloye, 2007).

Extreme dynamics

- 21 Alongside the “normal” functioning of high mountains, some phenomena of unusual intensity or character have been observed in the Alps for several years: large-scale rockfalls, increased frequency of small and mid-volume rockfalls, and acceleration, destabilisation or collapse of rock glaciers. The lack of past observations prevents saying with certainty that these are new phenomena, yet detailed case studies unequivocally connect them with global warming, mainly with warm events. Most of these phenomena could involve a risk to people and their homes, as well as to the infrastructures and sports activities on the high mountain slopes.

Large-scale rockfalls

- 22 Three large-scale rockfalls/small rock avalanches (volume > 0.1 million m³) have occurred over the past two decades in the Mont Blanc region where permafrost degradation has been mentioned as a possible trigger. The scar of the Brenva rock avalanche in January 1997 (2 million m³; Deline, 2009; Fig. 8b), located between 3400 and 3700 m asl. in a SE-facing rock wall, was probably characterised by warm permafrost (Deline *et al.*, submitted); a possible heat advection was probably able to induce localised permafrost degradation by circulating water along fractures at depth. It was probably the same for the Crammont case (0.5 million m³) in December 2008, which was a collapse from a N-facing slope between 2400 and 2650 m asl., also in a context of warm permafrost (Deline and al., 2011), and for the Bonatti Pillar event of June 2005 (0.26 million m³; Fig. 8a), which peaked at 3660 m asl. on the west face of the Drus (Ravanel and Deline, 2008).

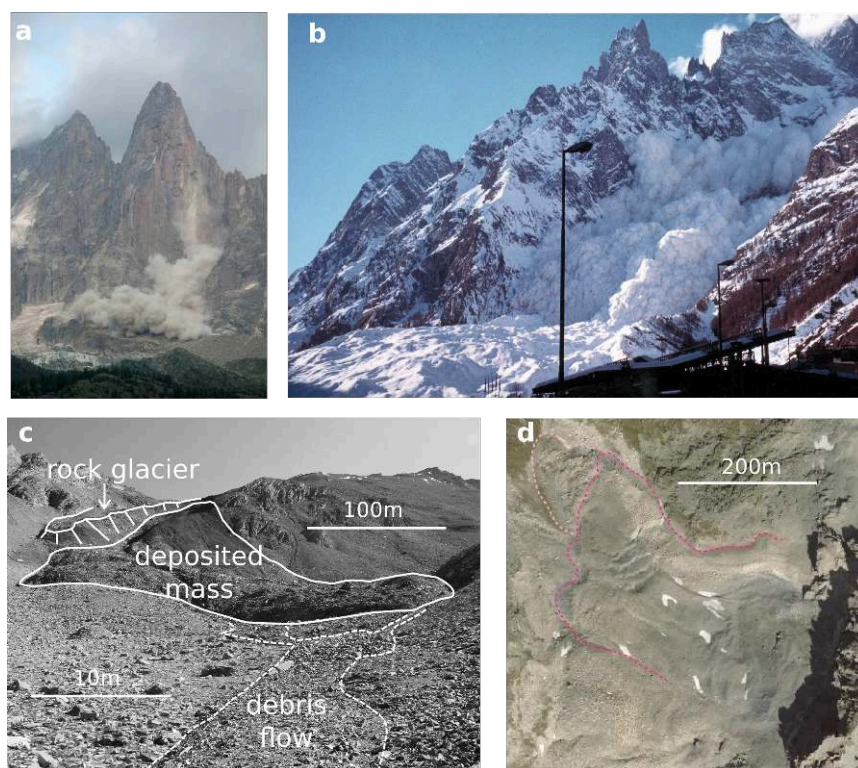
Destabilisation of rock glaciers

- 23 Many alpine rock glaciers have recently presented unusual modalities of movement, linked to an acceleration of all or part of the landform (Roer *et al.*, 2008; Delaloye *et al.*, 2012; Schoeneich *et al.*, 2014.). To date, the detachment of the Bérard rock glacier (Fig.

8c) in the French Alps is one of only two known cases in the world (Bodin *et al.*, 2012; Bodin *et al.*, accepted). The first signs of destabilisation date from at least 2004, followed by two major phases during the summer of 2006 that mobilised more than 0.25 million m³ of ice and rock debris. Besides the role of the topography, the causes cited are the increase in air temperature in the 1990s, heat waves in the summers of 2003 and 2006, and hydro-snow-weather conditions during the weeks preceding the detachment.

- 24 For the Vanoise massif, satellite data have recently enabled the detection of the destabilised Pierre Brune rock glacier (Fig. 8d) with clear signs of strong morphological deformations. A partial reconstruction of the phenomenon indicates that the first fractures appeared between 1952 and 1970 followed by an acceleration of the destabilisation between 1990 and 2001. GPS measurements have revealed current movements of several m.y⁻¹ (Echelard, 2014).

Figure 8. a) Rockfall on the west face of Les Drus (Mont Blanc massif) on 29th June 2005, around 11 AM (photo: J.-C. Bèche); b) Snow avalanche triggered by the Brenva rockfall (Italian side of the Mont Blanc massif) in January 1997 (photo: M. Pennard); c) Bérard rock glacier after its partial collapse in summer 2006 (after Bodin *et al.*, accepted); d) Fractures and chaotic topography of the Pierre Brune rock glacier (Vanoise massif) due to its destabilisation (after Echelard, 2014)



Cryokarstic processes

- 25 One of the effects of ice loss due to permafrost degradation is the development of “cryokarstic” phenomena, *i.e.* superficial subsidence due to a loss of volume in depth. Many cryokarstic forms have thus been observed on ski slopes. In most cases, they result from human disturbances (*e.g.* levelling works) that affect the active layer, with no direct link to climate change.
- 26 However, several natural cryokarsts have been observed in France in recent years. The most spectacular case is the Plan de Chauvet lake, in Haute Ubaye, which forms then

drains through the ice causing flash floods (Fig. 9). Six outburst floods have occurred since 1930, the most recent in 1997 and 2008. All the cryokarsts identified to date were formed in areas with probable permafrost, and many of them were set up in glacier forefields containing dead ice inherited from the Little Ice Age. Strictly, this corresponds to degrading glacial forms, but they affect icy bodies that have been maintained due to permafrost conditions.

Figure 9. Outburst of the Plan de Chauvet lake (Alpes de Haute Provence) in July 2008/ a) Overview of the proglacial margin that locally contains dead ice bodies in permafrost conditions; b) Draining sinkhole inside the ice ("moulin"); c) Flood related to the 2008 outburst some hundreds of metres downstream, where the Chauvet torrent meets the Ubaye river. Photos: M. Peyron, RTM 04, 2008



Discussion: is the emergence of new risks related to mountain permafrost degradation?

- 27 High mountains have always been concerned by natural hazards, due to the dynamics of the environment. Recent observations, however, show a significant increase in the frequency and/or intensity of some processes, such as rockfalls (Ravel and Deline, 2011). "New" phenomena have also been observed, such as the destabilisation of rock glaciers (Delaloye *et al.*, 2012) and the appearance of cryokarstic lakes.
- 28 Although it remains very difficult to predict large collapses, it is possible to identify potentially dangerous sites because of other phenomena. At the request of the RTM services (ONF), who are in charge of the management of natural hazards in mountain regions, a comprehensive inventory of rock glaciers has been carried out in the French Alps (Bornet *et al.*, in prep.). It is based on the interpretation of aerial photographs, orthophotos and field observations. The purpose of this inventory is to identify all the rock glaciers that are potentially dangerous and all the lakes in contact with rock

glaciers. A hazard assessment will then enable the setting up of a list of sites to be monitored.

- 29 Furthermore, an inventory of nearly 1,800 infrastructures (huts, lifts, paravalanches, fluid transport lines, *etc.*), located in the context of permafrost and/or glacial retreat in the French Alps, has just been completed. 10 % of these infrastructures show a high risk of destabilisation (Duvillard *et al.*, 2015, this volume). Damage has already been identified on many of them, sometimes with serious socio-economic consequences (closure and redundancy, declining turnover, necessary work, *etc.*).

Conclusions

- 30 Present in high-elevation rock walls and surficial deposits, the permafrost in France affects many slopes, and its degradation is likely to cause risks. The data available since 2009 have shown an increase in permafrost temperatures, linked to atmospheric warming and a deep snow cover during recent winters. According to the current monitoring and reconstructions of past events, geomorphological dynamics, associated with the presence of permafrost, seem broadly affected by permafrost warming as evidenced, for example, by the acceleration of rock glaciers in the 1990s. Moreover, extreme weather events, such as hot summers, are likely to result in peaks in geomorphological activity: the increase in the frequency of rockfalls in the Mont Blanc massif during summer 2003 or the destabilisation of the Bérard rock glacier in 2006 are probably good examples. The warming of permafrost and the related modification of ice or water contents in the soil clearly alter the conditions of stability of alpine slopes. However, understanding and predicting the consequences in terms of risks should take into account the very high variability of the local conditions in order to meet societal expectations, specifically those of natural hazard managers.

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ABSTRACTS

Alpine mountains are affected by significant geomorphological processes whose evolution is partly conditioned by permafrost warming: rockfalls of various volumes, destabilisation of rock glaciers, and cryokarst. These phenomena, because of their intensity, may generate risks for territories. This paper provides a synthesis of the knowledge about the current status of the mountain permafrost in the French Alps and its recent evolution. This state-of-the-art overview is based on research conducted over the past 10 years and the measurements collected within PermaFRANCE, the French network for long-term observation of the mountain permafrost. The analysis of the available data shows that for a rock wall located at 3800 m asl., the temperature is between -4.5 and -1.5°C at a depth of 10 m, according to the aspect, whereas it is close to the melting point in surficial deposits at 2800 m asl. on a northern slope. Since the beginning of these measurements at depth in 2010, a trend of increasing temperature has been discernible, as found in other alpine boreholes. As clearly shown by the surface measurements conducted since 2003, the thermal regime is influenced by snow, particularly in surficial deposits and to a much lesser extent in rock walls. This inter-annual variability is combined with longer-term trends, which probably induce the observed changes in geomorphological dynamics associated with alpine permafrost: an increased frequency of gravitational processes such as rockfalls and fluctuation in rock glacier velocities. The possible increase in extreme events, such as rock avalanches or the destabilisation of rock glaciers, in the coming decades could create new or increased risks, to which territories must thus adapt.

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Keywords: permafrost, French Alps, geomorphological dynamics, climate change

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