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Impacts of the 2003 and 2015 summer heatwaves on permafrost-affected rock-walls in the Mont Blanc massif

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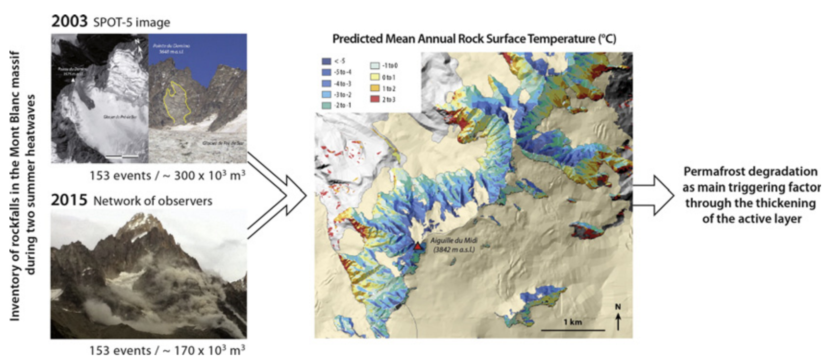
HIGHLIGHTS

- Exceptionally large numbers of rockfalls reported in the Alps in 2003 and 2015, years characterized by a summer heatwave.
- The frequency of rockfalls in summer 2015 was comparable to the one of summer 2003 in the Mont Blanc massif.
- Rockfalls occurred in permafrost-affected areas, generally at a shallow depth.

GRAPHICAL ABSTRACT



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ABSTRACT

Rockfall is one of the main geomorphological processes that affects the evolution and stability of rock-walls. At high elevations, rockfall is largely climate-driven, very probably because of the warming of rock-wall permafrost. So with the ongoing global warming that drives the degradation of permafrost, the related hazards for people and infrastructure could continue to increase.

The heatwave of summer 2015, which affected Western Europe from the end of June to August, had a serious impact on the stability of high-altitude rock-walls, including those in the Mont Blanc massif. A network of observers allowed us to survey the frequency and intensity of rock-wall morphodynamics in 2015, and to verify its relationship with permafrost. These observations were compared with those of the 2003 summer heatwave, identified and quantified by remote sensing.

A comparison between the two years shows a fairly similar rockfall pattern in respect of total volumes and high frequencies (about 160 rockfalls >100 m^3) but the total volume for 2003 is higher than the 2015 one (about 300,000 m^3 and 170,000 m^3 respectively). In both cases, rockfalls were numerous but with a low magnitude and occurred in permafrost-affected areas. This suggests a sudden and remarkable deepening of the active layer during these two summers, rather than a longer-term warming of the permafrost body.

1. Introduction

Since the late 1990s, numerous rockfalls and rock avalanches occurred in high Alpine areas worldwide (Evans and Clague, 1994; Noetzli et al., 2003; Huggel, 2008; Cox and Allen, 2009; Geertsema,

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2012). In some instances, involved materials contained a mixture of rock and ice with a volume exceeding 2×10^6 m^3, *e.g.* at Kolka Karmadon in the Russian Caucasus in 2002 (Huggel et al., 2005), at Punta Thurwieser in Italy in 2004 (Pirulli, 2009), or at Piz Cengalo in Switzerland in 2011 (Deline et al., 2015a). Many smaller rockfalls (*i.e.* $<0.1 \times 10^6$ m^3) have also occurred, *e.g.* at Mittlerer Burgstall in Austria in 2007 (Kellerer-Pirklbauer et al., 2012), or at the Aiguilles Marbrées in France in 2007 (Curtaz et al., 2014). Due to their steep topography, mountains are affected by significant gravity-related transfers of material, in particular by rockfall from rock-walls adjacent to glaciers (Fort et al., 2009). Rockfall is defined here as the detachment of a mass of rock with a volume exceeding 100 m^3 (Ravanel et al., 2010) from a steep rock-wall, along a series of discontinuities and its transportation downslope a variable distance (Deline et al., 2008). It is one of the most hazardous geomorphological processes because of its high velocity and the considerable volumes of rock involved. It threatens mountain infrastructure (Haeberli et al., 1997; Harris et al., 2001; Ravanel et al., 2012; Duvillard et al., 2015), and therefore tourism (Kellerer-Pirklbauer et al., 2012; Purdie et al., 2015) and, in the case of major events, can even threaten local populations in the valleys (Hewitt, 2004; Huggel et al., 2005; Clague, 2013; Einhorn et al., 2015; Haeberli et al., 2016).

There are many potential triggers (McColl, 2012), but three major factors – sometimes working in unison – generally trigger rockfalls in high mountains: seismic activity (Keefer, 2002; Jibson et al., 2004; Kargel et al., 2015), glacial debuttressing due to glacier retreat (Ballantyne, 2002; Dadson and Church, 2005; Oppikofer et al., 2008; Hewitt, 2009; Cossart et al., 2013) and permafrost degradation (Gruber and Haeberli, 2007; Harris et al., 2009). The latter refers to the warming of bedrock, the temperature of which is at or below 0 °C for at least two years (Dobinski, 2011). The modalities of permafrost degradation (Marchenko et al., 2007), successive or concomitant, are: (i) the warming of the subsurface layer and deepening of the active layer (Pogliotti et al., 2015), (ii) the warming of the permafrost body, with the possible formation of unfrozen pockets (*i.e.* taliks), (iii) the disappearance of the permafrost, especially at its lower altitudinal limit.

As well as the rise in bedrock temperature, permafrost degradation changes the physical properties of the interstitial ice. When the ice temperature approaches 0 °C, or when it melts, there is reduction in shear strength, loss of ice/rock interlocking, and ice segregation (Davies et al., 2001; Gruber and Haeberli, 2007; Matsuoka and Murton, 2008; Krautblatter et al., 2013). There is also an increase in the hydraulic permeability of the rock mass which can amplify ice segregation at the top of the permafrost layer *s.s.* (Draebing et al., 2017a; Murton et al., 2006).

While neither specifying the level of dependence between rockfall and permafrost warming, nor minimizing the role of other factors including passive ones (*e.g.* lithological setting and topography), several studies have highlighted the probable close relationship between rockfall and permafrost degradation, especially in marginal permafrost conditions. Fischer et al. (2012) investigated 56 high-altitude sites in the central European Alps where slope failures occurred during the last century; Ravanel et al. (2012) have investigated the stability of a rock ridge in the Mont Blanc Massif (MBM) over the past two decades; Allen et al. (2009) studied 19 bedrock failures that have occurred in the central region of the New Zealand Southern Alps since the mid-20th century; while Luethi et al. (2015) modelled rock temperature prior to 144 rockfalls in the European Alps. When rockfalls are individually studied after their occurrence, their trigger and their relation to the global warming is difficult to establish and verify: all these works indicate the high complexity of the processes involved (*e.g.* Deline et al., 2008, 2011; Phillips et al., 2016).

In high Alpine permafrost areas, several types of slope instability (*e.g.* rockfall, rock avalanche, rock glacier destabilisation, subsidence) are considered to be a result of the hottest periods on time scales of years to centuries (Evans and Clague, 1994; Harris et al., 2009; Borgatti and Soldati, 2010; Stoffel and Huggel, 2012; Huggel et al., 2012a; Bodin et al., 2015). A very high correlation has been established between periods of high temperatures and rockfalls in the MBM, for example on the west face of the Drus (Ravanel and Deline, 2008) and the north side of the Aiguilles de Chamonix (Ravanel and Deline, 2011). This correlation has been also demonstrated throughout the Alps (Huggel et al., 2012b).

A small number of studies identified the high number of rockfalls which occurred during the 2003 summer heatwave in the Alps (Schiermeier, 2003; Gruber et al., 2004a; Ravanel et al., 2011) and more generally the destabilizing impact of very hot periods or heatwaves (Gruber and Haeberli, 2007; Allen and Huggel, 2013; Paranunzio et al., 2016). These studies and others consider that future warm periods will strongly affect the permafrost and therefore rock-wall stability (Bottino et al., 2002; Chiarle and Mortara, 2008; Huggel et al., 2010). Nevertheless, no study has clearly and exhaustively established such an effect on the scale of a whole mountain range except Ravanel et al. (2011), even though, 12 years after the heatwave of 2003, Western Europe experienced another major summer heatwave in 2015.

Responding to the need for long-term monitoring of rockfall in permafrost-affected areas (Krautblatter et al., 2012; Hartmeyer et al., 2013), and in order to investigate the effects of heatwaves that provide tangible evidence of the effect of global warming (Schär et al., 2004; Seneviratne et al., 2013; Gobiet et al., 2014; Christidis et al., 2015) on rock-wall stability, we present here the results of our study into the rock-wall morphodynamics which occurred during the 2015 heatwave in the MBM, documented by a network of observers. These results have been compared with the morphodynamics of the 2003 summer heatwave, during which rockfalls were documented using their correlative deposits onto glacier surfaces, identified by satellite imagery.

2. Study area

2.1. The rockfall-prone Mont Blanc massif

The MBM (Fig. 1) covers an area of 550 km^2 on the outer margin of the Western Alps. About 30% of its area is covered by glaciers (Gardent et al., 2014) and permafrost is present throughout a large area (see below). Almost all of the MBM rocks are crystalline in nature (Von Raumer, 1999), Mont Blanc grained granite being intrusive within the Hercynian metamorphic series. A multiphase geological process generated shear zones, faults and fracture-lines (Bertini et al., 1985) that caused the large-scale deformation of the Mont Blanc granite. Hercynian and Alpine structures in the mountain range are mainly oriented N 0° to 25°E, and N 45° to 60°E, respectively.

Fracture-lines and steep topography make the MBM conducive to mass movements (Deline, 2009; Deline et al., 2012). It has been affected by several rock avalanches over the past few centuries, for which the possible role of permafrost degradation remains to be clarified. A large rock avalanche occurred for example in 1717 onto the Triolet Glacier, which dispersed a volume of *c.* 8.5×10^6 m^3 of debris over an area of 2.9 km^2 (Deline and Kirkbride, 2009). More recently, the Brenva glacier has experienced two major rock avalanches (Deline, 2001; Deline et al., 2015b); on the Grand Pilier d'Angle in 1920 (*c.* 3×10^6 m^3) and the Brenva Spur in 1997 (2×10^6 m^3). In recent years the MBM has also been affected by many small volume collapses (Deline et al., 2008, 2012; Ravanel and Deline, 2008; Ravanel et al., 2010, 2011, 2012).

2.2. The permafrost distribution in the Mont Blanc massif

In order to verify the hypothesis of the link between permafrost degradation and rockfall activity, knowledge of rock-wall permafrost distribution is required. A high-resolution map of rock-wall permafrost in the MBM has been produced (Magnin et al., 2015a). This map is based on the multiple linear regression model calibrated by Boeckli et al. (2012a) with >50 mean annual rock surface temperature (MARST) measurement points (MARSTmes) spread over the Alps. The statistical