Estimating glacier-bed overdeepenings as possible sites of future lakes in the de-glaciating Mont Blanc massif (Western European Alps)

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De-glaciating high mountain areas result in new landscapes of bedrock and debris where permafrost can degrade, persist or even newly form in cases, and of new lakes in glacier bed overdeepenings (GBOs) becoming ice-free. These landscapes with new lakes in close neighborhood to over-steepened and perennially frozen slopes are prone to chain reaction processes (*e.g.* rock-ice avalanches into lakes triggering impact waves, dam breach or overtopping, and debris flows) with potentially far-reaching run-out distances causing valley floors devastation. The frequency, magnitude and zonation of hazards are shifting, requiring integrative approaches combining comprehensive information about landscape evolution and related processes to support stakeholders in their adaptation strategies. In this study, we intend to setup an essential baseline for such an integrative approach in the Mont Blanc massif (MBM), which is a typical high-mountain range affected by de-glaciation processes. We first (i) predict and (ii) detect potential GBOs by combining the *GlabTop* model with a visual analysis based on morphological indications of glacier flow through over-deepened bed parts. We then (iii) determine the level of confidence concerning the resulting information, and (iv) estimate the approximate time range under which potential lakes could form. The location of the predicted GBOs and the shape of glacier beds are evaluated against currently forming water bodies at retreating glacier snouts, and seismic and ice penetrating radar measurements on the Argentière glacier. This comparison shows that the location of predicted GBOs is quite robust whereas their morphometric characteristics (depth, volume) are highly uncertain and tend to be underestimated. In total, 48/80 of the predicted or detected GBOs have a high level of confidence. In addition to five recently formed water bodies at glacier snouts, one of the high confidence GBOs (Talèfre glacier) which is also the most voluminous one could form imminently (during coming years), if not partially or totally drained through deeply incised gorges at the rock threshold. Twelve other lakes could form within the first half of the century under a constant or accelerated scenario of continued glacier retreat. Some of them are located below high and permanently frozen rock walls prone to destabilization and high-energy mass movements, hinting at possible hot spots in terms of hazards in the coming decades, where more detailed analysis would be required.

1. Introduction

The ongoing de-glaciation of high mountains has strong environmental and economic consequences (Field and Barros, 2014; IPCC, 2019). Glacier retreat yields new landscapes of rocks, lakes and unconsolidated morainic materials. New lakes bear economic opportunities associated with hydro-power production, fresh water supply or tourism (Haeberli et al., 2016a). However, they increasingly form at the foot of over-steepened and de-buttressed slopes. Additionally, melting of subsurface ice – *i.e.* permafrost degradation – tends to lower the stability of surrounding icy peaks, provoking slow as well as catastrophic downslope mass movements (*e.g.* Deline et al., 2015; Krautblatter et al., 2013; Harris, 2005). De-glaciating landscapes are therefore prone to chain reactions and far-reaching hazards, with for example high-elevated bedrock failures provoking impact waves in lakes and triggering debris or mud flows potentially devastating valley floors over large distances (*e.g.* Hubbard et al., 2005; Carey et al., 2012; Haeberli

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et al., 2017). The needs are thus growing for integrative assessment of environmental processes to support the adaptation of local communities (Huggel et al., 2015; Haeberli, 2017).

Assessing potential hazards associated with environmental changes in mountain areas first requires to systematically inventory the spatial and temporal distribution of cryospheric systems and landforms (*e.g.* glaciers, permafrost, glacial lakes), and events such as glacial lake outburst floods (GLOFs; Emmer, 2017; Portocarrero, 2014), rock-ice avalanches or debris flows. Such inventories are essential to point out possible areas or sites at risk where more detailed investigations would be necessary (GAPHAZ, 2017). Glacier inventories have been conducted for various regions of the world (*e.g.* Pfeffer et al., 2014), and in the frame of a global consensus (*e.g.* RGI Consortium, 2017). Mountain permafrost has been recently mapped for various mountain regions of the world (*e.g.* Boeckli et al., 2012; Gisnås et al., 2017; Magnin et al., 2019). Regional glacial lake inventories are also emerging (*e.g.* Worni et al., 2013; Emmer et al., 2015; Petrov et al., 2017), while their level of susceptibility to trigger GLOF events is generally studied at a more local scale (*e.g.* Worni et al., 2013; Allen et al., 2016; Falatkova et al., 2019). Different types of glacial lakes exist, depending on where they form (*e.g.* at the terminus, on later margins, below or at the surface of glaciers) and their damming material (*e.g.* Clague and O'Connor, 2015). Glacier-dammed lakes can outburst due to hydraulic or mechanical rupture (Clarke, 2003; Huggel et al., 2004), while dams consisting of moraines or landslide deposits are more vulnerable to breaching by rapid incision resulting from extreme precipitation, rapid snowmelt, earthquake, removal of the fine sediments or melting of buried ice (Clague and O'Connor, 2015). Bedrock thresholds are the most stable dams, but remain vulnerable to catastrophic outburst when impacted by rock or ice falls or avalanches (*e.g.* Worni et al., 2014). Recently, anticipating potential future lakes has become an emerging research field to detect possible areas at risks and support early planning of adaptation strategies. In this respect, the detection and characterization of glacier bed over-deepenings (GBO) is necessary (Haeberli et al., 2016b). In a first stage, morphometric analyses considering simple morphological criteria based on glacier-mechanical principles have been used to identify their location (Frey et al., 2010). In a second stage, glacier ice thickness models allowing to construct glacier beds and corresponding future "topographies without glaciers" have been employed for automatic detection of GBOs (*e.g.* Linsbauer et al., 2009, 2012, 2016) and combined with morphometric analysis for assessing their plausibility (Colonia et al., 2017). Prediction and analysis of GBO have been conducted over various mountain ranges worldwide (*e.g.* Linsbauer et al., 2012; 2016; Colonia et al., 2017; Kapitsa et al., 2017; Drenkhan et al., 2018), as a preliminary step to assess the risks and resources associated with de-glaciating landscapes (Drenkhan et al., 2019; Haeberli et al., 2016a).

In the Mont Blanc massif (MBM, Western European Alps), the increasing rock fall activity resulting from permafrost degradation is striking (*e.g.* Ravanel and Deline, 2011; Ravanel et al., 2010, 2017). At the same time, the acceleration of glacial retreat especially linked to the multiplication of summer heatwaves (Rabatel et al., 2013) deeply modifies the high mountain landscapes. Thus, the Mer de Glace – the largest glacier of the French Alps - loses each year several tens of meters in length (Vincent et al., 2014) and on average up to 3 m of ice thickness. Similarly to many other glaciers in this massif, the Mer the Glace tongue rapidly turns into a debris-covered glacier (Deline, 2005; Fig. 1). Next to the risk issue, these developments have strong impacts on tourism (Welling et al., 2015) and sports activities like mountaineering (Mourey et al., 2019). Recent research conducted in the MBM has therefore focused on assessing the current state and future evolution of the cryosphere (*e.g.* Gardent et al., 2014; Vincent et al., 2014, 2019; Magnin et al., 2015a, 2015b, 2017) and on detailed analyses of specific processes at particular sites to support hazard assessments, such as the Taconnaz hanging glacier from which large volumes of ice regularly break off, provoking high-magnitude ice avalanches (Vincent et al., 2015). However, integrative approaches to assess de-glaciating processes and related impacts are still missing.

This study intends to build up an additional step to help in developing an integrative assessment of the environmental processes taking place in the MBM. We predict locations and characteristics of potential glacier-bed overdeepenings (GBOs) in still ice-covered areas as possible locations of future lake formation in the MBM by combining automatic detection with the *GlabTop* model (standing for Glacier-bed Topography, Linsbauer et al., 2009, 2012; Paul and Linsbauer, 2012) and visual analysis based on morphometric criteria defined by Frey et al. (2010). We evaluate our predictions using existing Ice Penetrating Radar and seismic measurements (Vincent and Moreau, 2016), as well as newly formed lakes. We finally classify the level of confidence for each potential GBO and discuss possible timing for their formation. Bringing all this information together and combining them with current knowledge on permafrost and glaciers, we point out possible hot spots with respect to hazard potentials