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

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Abstract

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.

Keywords: high mountains, de-glaciating landscapes, glacier-bed overdeepenings, potential future lakes

Highlights

- Potential glacier bed overdeepenings (GBOs) in the Mont Blanc massif are studied
- Predicted locations and morphologies of GBOs are compared to field observations
- Levels of confidence are determined and ranked for each predicted GBO
- The timing of potential future lake (PFL) formation in GBOs is roughly estimated
- A baseline for an integrative risk assessment associated to PFL is given

1. Introduction

The ongoing de-glaciation of high mountains has strong environmental and economic consequences (Field et al., 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 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., in press). 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 in order to help setting priorities concerning monitoring and more detailed investigation.

2. The Mont Blanc massif: an emblematic de-glaciating high mountain range

The MBM is the highest and most glacierized massif of the French Alps with about 102 km^2 of glacier surface area on the French side (Gardent et al., 2014), extending from 1600 m a.s.l. (Glacier des Bossons front) to the Mont Blanc summit at 4809 m a.s.l. The 12-km-long Mer de Glace is the largest glacier, covering 30.5 km^2 in 2008 (Fig. 1 and 2). Its tongue spreads beneath the Montenvers tourist site while its ablation zone is now largely debris-covered (10% of the glacier surface area; Gardent, 2014). Like the other glaciers in the Alps, the MBM glaciers have experienced a general retreat since the end of the LIA despite small re-advances culminating in the 1890, 1920s and 1980s (Bauder et al., 2007, Haeberli et al., in press). Surface area loss for MBM glaciers has been more than 7% in two decades, from 109.5 km^2 in 1985 to 102.4 km^2 in 2008, in relation to the equilibrium line altitude of glaciers which is more and more often above 3000 m a.s.l. (Rabatel et al., 2013).

Large glacial lakes are not frequent in the MBM. About 15-20 small lakes exist and are damned by bedrock thresholds, moraines, or are located in depressions in gentle and vegetated terrains. Some proglacial lakes have recently formed in relation with glacier retreat. For example, two 95 and 150-m-wide lakes have formed in the 1990s in the Mer de Glace gorge-shaped forefield (Deline et al., 2012), but are now completely filled with sediment. Additionally, a proglacial lake was also mapped by the french *Institut National de l'Information Géographique et Forestière* (IGN) at the snout of the Pèlerins glacier, based on aerial photos from 2015. This lake is in morainic material and frequently drains like in 2016 (Google Earth image from July 2016). Similarly, during the 2010s, an unmapped likely non-perennial lake formed behind the (LIA) frontal moraine of the Arpette glacier (Switzerland). The scarcity of proglacial lakes in the massif is mainly a consequence of the present location of glacier fronts on rock ramps that are steep and smoothed by glacial erosion, and the homogeneous geological structure preventing the formation of large staircase-like counter-slopes favorable to lake formation (Deline et al., 2012).

Since the early 1990s, an increasing rock fall activity has been observed and systematically investigated in the MBM (Ravanel and Deline, 2013). Reconstruction of the rock fall history since the LIA has demonstrated the link between high rock fall occurrences and hot periods, as much at the decadal as at the seasonal scale (Ravanel and Deline, 2010). A comparison between the inventoried rock falls > 100 m^3 in 2003 (153 events) and 2015 (160 events) with a rock wall permafrost map (Magnin et al., 2015a) have shown a strong link between rock fall sources and warm permafrost areas (Ravanel et al., 2017). Regional atmospheric warming predicted for the 21st century suggests that warm permafrost in rock walls of the MBM will certainly extend up to 4300 and 3850 m a.s.l. in south and north faces respectively under a moderate climate scenario (RCP4.5; Magnin et al., 2017). The practice of mountaineering will thus be increasingly challenged (e.g. installing more and more equipment to maintain accessibility to huts, or closures of itineraries such as the access to the Mont

Blanc summit by the Goûter hut in 2015; Mourey and Ravanel, 2017), while damage to high mountain infrastructure is likely to multiply (Duvillard et al., 2019).

The MBM is therefore an emblematic de-glaciating high-mountain range prone to slope movement hazards and with strong implications for the local community. Adaptation to this changing environment is a key-challenge to mitigate risks, ensure perennial economical activities and define future resources.

3. Methods and data

The assessment of GBOs follows a 3-step approach: (i) predicting locations of potential GBOs with *GlabTop*, (ii) evaluating the prediction's performance, and (iii) analyzing the morphological characteristics of the landscape surrounding these GBOs to determine and classify their level of confidence. This last step also allows for identifying other potential GBOs not predicted with *GlabTop*. Finally, the time range under which potential future lakes could form at locations of identified GBOs is roughly assessed.

3.1. Predicting potential GBOs with *GlabTop*

In a first step, potential GBOs are identified by modelling glacier bed topography, which entails to model glacier ice thickness. Such modelling can be performed using different approaches, mainly depending on the available data and spatial scale of the study. Glacier ice thickness modeling has been done over single glaciers, mountain ranges or at global scale to estimate glacier geometries and ice volumes, which are a prerequisite to model scenarios of future glacier retreat and of related changes in water storage (*e.g.* Huss and Farinotti, 2012; Vincent et al., 2014; Farinotti et al., 2016; Zekollari et al., 2018). Distributed glacier thickness models relate ice thicknesses to surface slopes via basal shear stresses by either assuming a general relation with glacier mass turn-over (*e.g.* Haeberli and Hoelzle, 1995; James and Carrivick, 2016; Linsbauer et al., 2012), or on mass conservation and ice flow dynamics (*e.g.* Farinotti et al., 2009, 2017). Uncertainties in absolute values of predicted local ice thicknesses reflect the difficulties of realistically parameterizing mass fluxes at the surface (mass balance), within the ice (deformation) and at its base (sliding, bed deformation). They tend to be random, locally high (a range comparable to the observed ice thickness), and about 30 % for mean values of large samples (Farinotti et al., 2017). In contrast, relative spatial differences of predicted ice thicknesses and related locations of glacier bed overdeepenings are assumed to be less uncertain as they are more directly related to glacier surface slope (Frey et al., 2010) that can be realistically derived from DEMs. The appropriate spatial smoothing function to account for longitudinal stress coupling within glaciers, however, remains a source of considerable uncertainties (Adhikari and Marshall, 2013).

The efficiency of *GlabTop* (Linsbauer et al., 2012; Paul and Linsbauer, 2012) and *GlabTop2* (Frey et al., 2014) to estimate possible GBOs over large areas (*e.g.* Linsbauer et al., 2016) have been demonstrated on various mountain ranges as they are simple, transparent, robust, and easily accessible. These two model versions mainly require glacier outlines and a DEM to calculate ice thickness from surface slope *via* the basal shear stress which is assumed to be constant within individual glaciers but do depend on their elevation range governing overall mass turn-over. The original *GlabTop* model requires to manually digitize branch lines along which ice thickness is estimated. *GlabTop*2 is fully automated with ice thickness estimated at random points over the glaciers. This makes *GlabTop2* more appropriate for applications in extremely large areas with numerous glaciers such as the Himalayas (Linsbauer et al., 2016) since no manual task is required. For the MBM, *GlabTop* was preferred as manual digitalization was easily feasible and provided intimate knowledge of the treated glaciers and their characteristics. However, digitizing branch lines is a critical and important step as these branch lines define the locations where the ice thickness is estimated. In Paul and Linsbauer (2012) various tests on this issue have been performed and recommendation and rules for a best practice of digitizing branch lines were given. According to these guidelines, the branch lines were digitized from bottom to top, perpendicular to the contour lines of surface elevation, ending about 100 m before the glacier outline with one parallel line for every 200–400 m of glacier width. Additional branch lines covering glacier tongues may result in higher ice volumes and deeper and wider GBOs but would not have a general influence on the general picture of the ice thickness distribution. The resulting *GlabTop* model of distributed glacier ice thicknesses were subtracted from the current DEM-based topography in order to generate a DEM without glaciers, which allows identification of subglacial overdeepenings.

For this study, we run *GlabTop* with glacier outlines drawn within the *GlaRiskAlps* project (*http://www.glariskalp.eu*) and three different DEMs providing their respective output to help in assessing the robustness of the predicted GBOs. Details of these data are given in Table 1. The three DEMs are built upon various sources of data collected between 2000 and 2010.

	DEMs		
	IGN (*Institut National de Géographie*)	**RGD (*Régie de Données de la Haute Savoie*)**	**ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer)**
Resolution	25	20	27
Date of data acquisition	2000 - 2010	2008	2000-2008
Spatial coverage*	French and Italian sides	French side	Entire MBM
	Glacier outlines of the MBM		
	France	**Italy**	**Switzerland**
Source of data	Orthophotos	Spot5	Airborne photos
Date of data acquisition	2008	2002 - 2015	2008 - 2011
Reference	Gardent *et al.* (2014)	fondazionemontagnasicura.org	Fischer *et al.* (2014)

Table 1. Details of the topographical and glacier inventory data used to run *GlabTop*. * The spatial coverage of the respective DEMs is visible in Figure 3.

3.2. Evaluation of *GlabTop* output

Evaluation of the *GlabTop* output is conducted in two steps, which provide information about the model performance. First, an independent data set of Ice Penetrating Radar (IPR) and seismic measurements collected on the Argentière glacier is used to compare the predicted with the measured ice depth and subglacial bedrock topography. Seismic measurements were acquired between the 1950's and the 1970's and provide bedrock topography with an uncertainty of ± 10 m (Vincent and Moreau, 2016). IPR measurements were acquired between 2013 and 2015 with 4.2 MHz transmitting and receiving antennas (Rabatel et al., 2018). A total of 1246 IPR measurement points collected along

20 transversal profiles, and 181 seismic measurement points along one lengthwise profile are available for evaluation. We therefore extract predicted subglacial bedrock elevations at all measured bedrock elevation points to quantify the global uncertainty for the Argentière glacier. The general uncertainty of predicted ice thicknesses according to various models including *GlabTop* has been already assessed in a comparative study by Farinotti et al. (2017; see sect 3.1), but the existence of field data is a unique opportunity to evaluate *GlabTop* performances and limitations at the scale of an individual glacier and to assess the implications for the interpretation of the results. This helps determining limits in the depths, volumes and shapes of predicted GBOs.

In a second step, we compare the predicted GBOs at locations of recently deglaciated forefields and analyze the conditions under which lakes have formed or not. This analysis is feasible because *GlabTop* runs with glacier outlines drawn from data collected in the late 2000's – early 2010's, and which are therefore not representing the current glacier extension. The new lakes are recognized using Google Earth images. For all predicted GBOs in already de-glaciated forefields, we perform a morphometric analysis based on two out of four criteria identified by Frey et al. (2010) to determine the likelihood of a GBO to exist below the glacier surface: (i) the slope angle (generally below 5 to 10°) at the location of predicted GBOs, and (ii) the absence/presence of a bedrock threshold. The slope angle for criterion (i) is calculated using GIS tools with the IGN and ASTER DEMs. It is first calculated for each cell and is then filtered across 8 adjacent cells in order to smooth the slope gradient and possible artefacts or isolated pixel cells. We use the slope angle calculated from the IGN DEM in priority as this is the one with best ratios between spatial coverage and artifacts, and we complement this information from the ASTER DEM outside the IGN DEM boundaries. This analysis points out other lakes forming on glacier margins, which can also be used to evaluate *GlabTop* output.

3.3. Morphological analysis and classification of the predicted GBOs likelihood

For all predicted GBOs > 1 ha, except those analyzed in the evaluation step, we examine the four morphological criteria determined by Frey et al. (2010). According to these criteria, a predicted GBO is very likely to exist if:

(i) the slope angle at its location its relatively low (generally < 5 to 10°),

(ii) a break in slope is found downstream of the predicted GBO,

(iii) a bedrock threshold and/or reduction in glacier width is visible downstream, and

(iv) a transition from a crevasse-free area to a crevasse field indicates a transition from compressing to extending flow.

For each criterion, a value ranging from 0 to 5 is given to define its intensity and obviousness. For criteria (i) and (ii), the values are determined based on quantitative information (slope angle values within the GBOs' surface areas), while for criteria (iii) and (iv) the values are attributed based on a visual analysis (obviousness of the crevasses and bedrock threshold; Tab. 2). These quantitative and qualitative thresholds are subjectively determined in order to support a differentiated inter-comparison of the confidence levels related to predicted GBOs in this study. The slope angle used for analyzing criteria (i) and (ii) is calculated as described in section 3.2. For criteria (iii) and (iv), we use Google Earth images.

Value attributed to each criterion	(i) Slope angle at predicted GBOs	(ii) Break in slope angle	(iii) Bedrock threshold / Glacier narrowing	Transition from no crevasse to a field of crevasse
0	< 20 % < 20°*	< 20 % > 5° **	None	None
1	> 20 % < 20°	> 20 % > 5°	↓	↓
2	> 50 % < 20°	> 50 % > 5°		
3	> 50 % < 15°	> 50 % > 10°		
4	> 50 % < 10°	> 50 % > 15°		
5	> 50 % < 5°	> 50 % > 20°	Obvious	Obvious

Table 2. Summary of the morphological analysis and classification criteria to determine the level of confidence of predicted GBOs. * Less than 20 % of the glacier surface area above the predicted GBOs has a slope angle < to 20°. ** Less than 20 % of the downstream surface area has a slope angle change < 5°.

As a result, the total value for each GBO can reach a maximum of 20 (5 for each of the 4 criteria). However, for some GBOs, not all criteria can be analyzed, such as the existence of crevasses under heavy debris cover for example. Therefore, if only 3 criteria are analyzed, the total value can only reach 15 (5 for 3 criteria). In order to compare the different levels of confidence of the predicted GBOs, the percentage of cumulated value relative to the possible maximum total value is calculated for each GBO. The closer the predicted GBOs are to 100 %, the most likely they exist. Then, the level of confidence of each GBO is classified from 0 to 5 as follow:

- < 10 % = 0
- 10 to 30 % = 1
- 30 to 50 % = 2
- 50 to 70 % = 3
- 70 to 90 % = 4
- ≥ 90 % = 5

A value of 0 concerns areas were none of the morphological criteria can be clearly observed. Modelled GBOs are therefore disregarded in such cases. The applied classification allows to limit the effects of subjectivity in the criteria attribution and helps pinpointing high-confidence predictions. Whether a lake will form in such cases still depends on the presence or absence of a deeply cut drainage gorge at its lower end. Such narrow features cannot be predicted by any model at present. GBOs are therefore always sites of “potential lake formation”.

3.4. Visual identification and classification of other potential GBOs

The morphological analysis conducted on predicted GBO highlights possible other locations for potential GBOs that are not predicted with *GlabTop*. When modeling the ice thickness and as a derivative the locations of potential GBOs with *GlabTop*, the main factors are the slope of the input DEM and the positions of the branch lines. Positioning and amount of parallel branch lines define the locations to estimate the ice thickness and surface slope is averaged within 50 m elevation bin along these branch lines. It is therefore possible that flat glacier parts or breaks in slope are smoothed out and cannot be detected by the model. Glacier tongues may also be critical for GBO prediction, when glacier outlines and DEM do not correspond in detail. Furthermore, *GlabTop* does not take into account glacier width reductions or crevasses, which are important parameters in the visual analysis. All these limits explain that in some cases, potential GBOs are not predicted with *GlabTop*.

We therefore conduct a complementary analysis based on criteria (i) and (ii). For areas combining a slope class (criterion (i)) and a break in slope class (criterion (ii)) ≥ 3, we manually draw potential GBO on the concerned area. For these other potential GBOs, we then perform the same morphological analysis and classification as for those predicted with *GlabTop*.

3.5. Assessing the time range for formation of potential future lakes

In order to provide a rough estimate of the possible timing for possible future lake formation and refine estimation of potential hot spots regarding associated risks and opportunities, we extrapolate the observed glacier retreat between the 1970s and the recent period. Details of the glacier contour lines used to calculate glacier retreat rate are given in Table 3. For each glacier, we calculate the rate of horizontal retreat based on the glacier length change between the reference years of the 1970s and the 2000s. We then compute an average annual retreat rate to extrapolate the glacier retreat from the present-day glacier margins to the down-valley end of the predicted GBOs in order to obtain straightforward and simple first-order scenarios of the onset of potential future lake formation. For the Mer de Glace and Argentière glacier we furthermore use a recent degree-day model of future glacier retreat considering one conservative Representative Concentration Pathway of greenhouse gas emissions (RCP 4.5) to refine our estimations (Vincent et al., 2019).

	France	**Italy**	**Switzerland**
Source of Data	IGN maps (Scan 25®)	Aerial photos	Aerial photos
Date of data construction	1967-1971	1975	1973
Years of reference for retreating rate calculation	1970 - 2008	1975 - 2010	1973 - 2010
Reference	Gardent et al. (2014)	fondazionemontagnasicura.org	Müller et al. (1976) ; Maisch et al. (2000) ; Paul (2004)

Table 3. Details of the glacier outline data used to reconstruct the glacier retreat rate since the 1970's.

Following the approach used by Colonia et al. (2017), we express the estimated likely onset of lake formation with respect to four time classes:

- underway (this mainly concerns the – in cases partially – existing water bodies already identified with observations described in sect. 3.2.),
- imminent, which refers to the predicted GBOs which are appending the glacier margins, or
- before or around mid-century.

Given the high uncertainty in our approach – we only consider one glacier parameter (length) and assume a constant retreat over time – it is hardly relevant to consider strict time thresholds for defining "mid-century". Assuming that the future glacier retreat is likely to accelerate due to projected enhanced global warming, especially in high mountain areas (MRI, 2015), we rather express the last time class according to three possible scenarios:

- under constant retreat,
- under accelerating retreat by a factor of 1.5 or RCP 4.5 (slight acceleration), or
- under accelerating retreat by a factor of 2 (strong acceleration).

We therefore do not intend to deliver strict time ranges but rather to provide a baseline to refine the classification of potential hot spots.

4. Results

We here present the occurrence and approximate characteristics of the predicted GBOs, the results of the evaluation against measured glacier bed topography and recently retreated glacier snouts, the outcomes of the morphological analysis (classification of GBOs likelihood and other potential GBOs), and finally, the rough timing under which potential future lakes could form. Beyond assessing GBOs, *GlabTop* also offers the possibility to assess and discuss the glacier ice thickness and distribution in the MBM, which is out of the scope of this study and is therefore provided in the Supplements (S1).

4.1. Occurrence and approximate characteristics of the predicted GBO

Between 40 and 50 GBOs > 1 ha are modelled, depending on the applied DEM (Fig. 3; Tab. 4). The larger ones are predicted with all three DEMs, but in some cases, two to three small GBOs are predicted with one DEM, while a single large GBO is predicted with the other DEMs (*e.g.* at the confluence between the Leschaux and Tacul glaciers feeding the Mer de Glace; Fig. 3). The ASTER DEM predicts 7 more GBOs than the IGN DEM, and most of these additional GBOs are relatively small and located under the Géant and Bossons glaciers. The GBO predicted with the ASTER DEM at the top of the Bossons glacier is a DEM artefact resulting from data voids forming a hole (depth of 285 m). It was removed from the statistics in Table 4.

GBOs are predicted at the base of strongly different glacier types and areas: trunk glaciers such as the Argentière and Miage glaciers, tributaries such as the Tacul glacier, at glacier confluences such as the Tacul and Leschaux glaciers, under cirque glaciers such as the Talèfre glacier or below "ice-cap like" glaciers such as the Plateau du Trient glacier. The Argentière glacier is remarkable for the numerous GBOs which are spread all along its length.

The depth of the predicted GBOs varies significantly from one DEM to another (Linsbauer, 2013; cf. figure 2 in Haeberli et al., 2016b), the IGN DEM predicting the deepest, largest, and most voluminous ones, while the shallowest and least voluminous GBOs are predicted with the ASTER DEM. The ASTER DEM suffers from local artifacts, especially in flat glacier parts where the surface is not as smooth as in the IGN DEM. This results in higher mean slopes for the ASTER DEM and hence less variability in ice thickness and therefore shallower GBO's. Most GBOs have a surface area < 10 ha (Fig. 4), and two have a surface area close to 40 ha according to the IGN DEM. About 75% of the GBOs have a maximum depth < 40 m with the IGN DEM and < 30 m with the ASTER DEM. The mean depth ranges around 10 m for half of the GBOs, while their mean volume is < 1 Mm^3. About 25% of the GBOs predicted with the IGN DEM have a calculated volume ranging from 2.5 to 5 Mm^3, and the most voluminous are 6, 7, 13 and 19 Mm^3, but 6 Mm^3 maximum with the ASTER DEM. The predicted GBOs represent about 2.5% and 1.8% of the total glacier surface area with the IGN and ASTER DEMs, respectively.

The deepest GBO is found at the tongue of the Tré-la-Tête glacier with all three DEMs. The largest and most voluminous one is located at the bottom of the Talèfre glacier with the IGN and ASTER DEM. However, the RGD DEM predicts the most voluminous lake on the Argentière glacier with 6.8 Mm^3 (the 3^{rd} lowest one) and the deepest and largest one also at the bottom of the Talèfre glacier with 30.7 ha).

	ASTER DEM	**IGN DEM**
Number of predicted overdeepenings > 1 ha	49	42
Mean depth (m)	10.2	14
Mean maximum depth (m)	23.2	33.8
Maximum depth (m)	70	102
Mean surface area (ha)	5.9	9.5
Maximum surface area (ha)	32.7	43.8
Total surface area (ha)	287.7	398.3
Mean volume (Mm^3)	0.8	2.1
Maximum volume (Mm^3)	6.1	19.2
Total volume (Mm^3)	39.2	89.7

Table 4. Summary statistics of the predicted GBOs with the ASTER and IGN DEMs. Statistics are not provided for the RGD DEM because it does not cover the Swiss and Italian sides of the massif. Statistics with the IGN are slightly biased because the IGN DEM does not cover the lowest part of the Swiss glaciers (see Fig. 3).

4.2.Evaluation of *GlabTop* output

IPR and seismic measurements are used to determine the limitations in predicted GBOs morphometrics by comparing the measured bedrock topography with the predicted one, while the comparison of GBO locations with recently formed water bodies rather determines the robustness in predicted GBO locations.

4.2.1. Evaluation of the predicted glacier bed topography at Argentière glacier

The measured bedrock elevation from IPR and seismic measurements (Vincent and Moreau, 2016; Rabatel et al., 2018) is compared to the predicted bedrock elevation according to the three DEMs for

1246 transversal and the 181 lengthwise measurement points available on the Argentière glacier (Fig. 5). Overall, *GlabTop* in this case tends to underestimate ice thicknesses and to provide too high bed elevations in the upper parts of the glacier. The difference is rather constant and similar for the three applied DEMs, with high statistical correlations between the measured and predicted data (Fig. 5b). The calculated difference between the measured bedrock elevation and the predicted one at each measurement point has a median ranging from -180 (ASTER DEM) to -150 m (RGD DEM; Fig. 5c), while the mean is slightly lower (from -155 to -130, respectively). Locally, differences up to -300 m are observed, and are greater in the higher part of the glacier (Fig. 6: Profiles 3-5) than in its lower part (Fig. 6: Profiles 1-2). The shape and elevation of the predicted bedrock is very similar with all three applied DEMs (Fig. 6), but does not fully reflect the characteristic deeply-cut through cross profiles detected with the IPR measurements, nor the more or less steep counter-slopes delineating the basin-shaped GBO highlighted by the seismic measurements (Profile 1 on Fig. 5 and 6). As a result, the depth of the predicted GBO is underestimated by about 100 m, and the predicted volume (2.8 to 3.7 Mm^3 depending on the DEM) is about four times smaller than the 12 Mm^3 estimated from glacier bed measurements (Vincent et al., 2019). The large local differences produced by the stress-related *GlabTop* approach are comparable to results from simulations using the flux-related approach by Huss and Farinotti (2012; cf. Figures 6 and 7 in Rabatel et al., 2018). They are nevertheless extreme (around 60% of the estimated value) in the present case, exceed uncertainty ranges commonly reported from inter-comparisons at other glaciers (Linsbauer et al, 2012; cf. also Farinotti et al. 2017, 2019) and need further analyses. This illustrates the still large uncertainty related to modeled absolute values of bed elevations and the resulting limitations to interpret and use predicted GBOs morphologies for further applications (cf. Langhammer et al:, 2019).

4.2.2. Predicted overdeepenings in recently deglaciated forefields

The glacier outlines used in this study have been constructed on the basis of ortho-photographs from 2008 (BD Ortho® from the IGN). Since 2008, glacier retreat has already uncovered terrains with new water bodies at some forefield sites. A visual analysis has enabled the detection of 5 new water bodies forming in the forefields of retreating glaciers: at Pèlerins, Tré-la-Tête, Triolet, Bionnassay and A

Neuve glaciers. These 5 water bodies correspond to predicted GBOs (Fig. 7). Additionally, 1 small ice-marginal lake has been recently unveiled with the narrowing of the Bossons glacier, where no GBO is predicted. This lake was actually observed by other research teams during summer 2012 when the glacier also narrowed before thickening the following years (personal communication from J. Berthet). Finally, 3 predicted GBOs in recently de-glaciated forefields do not match with recent water body formation: d'Orny glacier, Estelette glacier and Mer de Glace (Fig. 8).

The morphological analysis conducted with criteria (i) and (iii) which are related to the slope angle at predicted GBOs locations and the possible existence of bedrock threshold reveals that the two glacier forefields where no water body was found correspond to the GBOs with the lowest predicted volumes and the shallowest maximum depth (Tab. 5). For these two GBO, the glacier surface is relatively steep (mostly > 10°, value of 3 for criterion (i)) and no bedrock threshold is found.

Interestingly, some water bodies have formed below relatively steep glacier surfaces (value of 3 for criterion (i)), such as at the Bionnassay glacier toe for example, but for these cases, a bedrock threshold can be identified.

In the forefield of the Tré-la-Tête glacier, a water body is visible on the side and at the tip of the glacier front (Fig. 7), hinting at a larger body below the glacier front. It is located in a < 10° slope and is dammed by a bedrock threshold. At the Pèlerins glacier, the water body forming within morainic debris was visible in 2015 (Fig. 7) but disappeared the following year. The slope of this glacier front is mostly > 10°, there is no bedrock threshold and the water body has formed behind an ice cliff and in certainly temporarily frozen (unpublished information) and impermeable morainic material, making a small dam which could have thawed and/or resorted the following year.

The lake forming at the Bossons glacier is not predicted with *GlabTop*, most probably due to the design of the branch lines which have not covered this side of the steep glacier as explained in section 3.4 and further discussed in section 5.2. It is however detected when conducting the morphological analysis (sect. 4.4).

These observations seem to indicate that *GlabTop* realistically predicts locations of GBOs, and that the combination of a surface slope $> 10°$ (criterion (i) < 3) and the absence of a bedrock threshold (criterion (iii) ≤ 1) does not permit the formation of a perennial lake. The spatial distribution of these predicted GBOs is visible on Figure 9.

Glacier	A Neuve		Triolet		Tré-la-Tête		Bionnassay		Pèlerins		d'Orny		Estelette		Mer de Glace	
DEM	**IGN**	**AST.**	**IGN**	**AST.**	**IGN**	**AST.**	**IGN**	**AST.**	**IGN**	**AST.**	**IGN**	**AST.**	**IGN**	**AST.**	**IGN**	**AST.**
Recently formed water body	YES		YES		YES		YES		YES		NO		NO		NO	
Slope angle class (0 to 5)**	*O.b	3	4	4	4	4	3	3	4	4	*O.b	3	3	-	3	2
GBO max. depth (m)	*O.b	19	40	39	33	21	-	22	24	19	*O.b	16	16	-	24	14
GBO mean depth (m)	*O.b	11	22	17.9	13.2	8.2	-	10.5	9.8	9.2	*O.b	7.6	7.2	-	10.7	7.2
GBO surface area (ha)	*O.b	1.8	8.2	4.9	5.1	7.4	-	2.8	8	3.5	*O.b	1.6	16.2	-	2	1.4
GBO volume (Mm^3)	*O.b	0.2	1.8	0.9	0.7	0.6	-	0.3	0.8	0.3	*O.b	0.1	0.1	-	0.2	0.1
Observations on the damming material (bedrock threshold class (0 to 5), moraine)**	Water body in morainic material, behind a bedrock threshold (4)		Water body in morainic material behind a bedrock threshold (4)		Water body behind a bedrock threshold (3)		Water body behind a bedrock threshold (3)		Water body in morainic material. Was present in 2015 but not in 2016. No bedrock threshold (0)		Floodplain, no bedrock threshold (0)		Floodplain, no bedrock threshold (0)		Morainic material in a gorge and dejection cone, no bedrock threshold (0)	

Table 5. Characteristics of the recently formed water bodies at predicted GBOs. * O.b = "out of DEM bound"; ** See Tab.2

4.3. Morphological analysis of predicted GBO

In this section, 41 GBO predicted with *GlabTop* are analyzed and classified into 5 different levels of confidence based on the four morphological criteria described in section 3.3. The detailed results of the evaluation are provided in the Supplements (S2) and only the final classification is reported in Figure 9.

Among the 41 predicted GBOs, 7 have a level of confidence reaching 5/5, 15 have a value of 4/5, 10 have a level of confidence of 3/5, 6 have a value of 2, and 3 have a value of 1. For these last three, criteria (ii) and (iv) were not observed, reducing the maximum total value to 10. The deepest (Tré-la-Tête glacier) and most voluminous (Talèfre glacier) GBOs have both a level of confidence reaching a value of 5/5. In accordance with findings from the previous section, the predicted GBOs with lowest levels of confidence (≤ 2) are those without bedrock threshold.

4.4. Other potential GBOs detected by visual analysis

By mapping the slope angle to perform the morphological analysis of the predicted GBOs with *GlabTop*, 39 additional areas have been spotted as possible locations for GBOs (Fig. 9). All areas with criteria (i) and (ii) ≥ 3 are therefore inventoried and analyzed in more detail following the same approach as for predicted GBOs (details of the analysis provided in the Supplements (S3)). For these 39 areas, only one reaches a level of confidence of 5/5 (on the Bionnassay glacier), 9 have a value of 4/5, 17 have a value of 3/5, 12 have a confidence level of 2/5. Lower confidence levels are not found because these potential GBOs were detected with a minimum value of 30 % of the criteria filled (3 and 3 for criteria (i) and (ii) respectively, on a maximum total value of 20). However, conversely to the GBOs predicted with *GlabTop*, the majority of potential GBOs detected by visual analysis have a rather low (≤ 3) level of confidence.

4.5. Possible timing for potential future lake formation

The 5 water bodies identified at the recently de-glaciated forefields in sect. 4.2.2 are considered to be 5 cases with lake formation "underway". However, it is noteworthy that the water body forming at the

Pèlerins glacier is not perennial due to the absence of a consolidated dam or possibly also, the high permeability of the lake bottom in thick morainic debris (sect. 4.2.3).

When extrapolating recent glacier retreat (1970's – 2000's), 3 potential future lakes predicted with *GlabTop* are imminent in a context of constant or accelerate retreating rate, at the Talèfre glacier (level of confidence of 5), the two other being at the Miage glacier (very low level of confidence). However, it is noteworthy that the bedrock threshold damming the potential future lake at the Talèfre glacier is incised by deep gorges (Fig. 10) which suggest that the lake depth could be smaller than expected, if the lake is not totally drained away. Under constant or accelerating glacier shrinkage, one to two lakes could form at the Triolet glacier before the mid-century (Fig. 11). Other lakes with high levels of confidence could eventually form before or by mid-century at the Argentière and Tour glaciers if glacier shrinkage slightly accelerates. For the Argentière glacier, this timing is confirmed by the degree-days model from Vincent et al. (2019). But the Argentière glacier is a particular case because the lowest glacier tongue has recently detached from its upper part at a bedrock threshold. The lowest glacier tongue, now isolated from the trunk glacier, is still fed by ice falls from the upper glacier part now terminating on a pronounced bedrock riegel. However, ice-feeding could stop by 2035 due to further retreat of the trunk glacier, and the predicted GBOs with a rather low level of confidence in the isolated "dead" glacier body could form much earlier than reported on Figure 11 which only reports calculations based on linear extrapolation of glacier retreat rate.

When considering the potential other lakes detected by visual analysis, one lake could form imminently at the Lée Blanche glacier (level of confidence of 2) under constant glacier retreat. One lake at the Estelette and another one at the Bossons glacier (respectively 3 and 4 for the level of confidence) could form before mid-century or imminently if the glacier retreat accelerates by a factor of two. At the Bossons glacier, it is noteworthy that the lowest potential lake detected by visual analysis is right above a narrowing of the glacier width corresponding to a major break in slope and a related ice fall, similarly to the Argentière glacier tongue detachment. This lake has been already observed in 2012 (J. Berthet, personal communication), and may appear and disappear depending on glacier fluctuation, but will certainly form when glacier will have retreated by mid-century (Fig. 10).

At the Frebouze, Jetoula, Lée Blanche, Gruetta, A Neuve and Treutse Bô glaciers (level of confidence of 4 or 3), new lakes could also form around mid-century if the glacier retreat rate doubles. Other lakes with levels of confidence of 3 or 4 could also form at the Jetoula, at the Lée Blanche (a third lake), or Treutse bô glaciers around mid-century if the glacier retreat rates double.

5. Discussion and perspectives

5.1. Implications of the results to anticipate potential GLOFs

Compiling a potential future lake inventory is a crucial step to develop an integrative approach of potential future risks and opportunities related to de-glaciating landscapes. Such investigations are increasingly developed in high mountain ranges in order to anticipate GLOFs. In comparison to other mountain areas where *GlabTop* has been applied, the ratio between modelled volume of glacier ice and modelled volume of GBOs is considerably smaller in the MBM than in the Himalaya-Karakorum for example (Linsbauer et al., 2016). With about 0.5-1% of the glacier volume, predicted GBOs in the Mont Blanc massif are more similar to the Peruvian Andes that are characterized by a limited extent of flat glacier areas (Colonia et al., 2017). However, conversely to the Peruvian Andes, glacial lakes have not grown much within the past decades of glacier retreat in the MBM, and the majority of potential future lakes will not grow imminently. This difference in the timing of glacial lake development explains that the Peruvian Andes have faced repeated GLOF events (Carey et al., 2010; Portocarrero, 2014, Emmer, 2017) while this threat could likely increase within the coming decades in the MBM. Many glacier tongues are still hanging in rock ramps in the MBM (*e.g.* Bossons glacier), while trunk glaciers occupy rather steep valleys with prominent gorges at their outlet (*e.g.* Mer de Glace and Argentière glacier). This probably explains the restricted lake development within the past and coming decades compared to some other high mountain ranges. However, small lakes have formed and will probably form in staircase-like bedrock slopes (*e.g.* at the Bossons glacier), while larger lakes will possibly form in flatter areas in the coming decades where glacier tongue detach from bedrock thresholds (*e.g.* Talèfre or Argentière glaciers) or later, when glacier margins will have reached higher areas with less steep profiles.

Thus, due to its specific topography, the MBM massif has not yet experienced a remarkable growth in new lakes but such landscape features will possibly develop in the near future and constitute some new risks and options. The first-order estimation proposed in this study is therefore an essential basis to identify potential hot spots and prioritize sites to be investigated in more details. Before considering further applications of the results, it is however necessary to consider limitations in the here proposed approach.

5.2. Limitations in the approach

The modeled ice thicknesses at Argentière glacier better fit measured data in the lowest glacier part, but the strong underestimation of modeled ice thicknesses in the upper part of the glacier is not easily explained. Adjusting the basic assumptions in the *GlabTop* model to correctly reproduce the measured bed elevations at these locations would necessitate an increase of the assumed average basal shear stress from 150 kPa to some 200 to 250 kPa, a value which is at least at the upper limits of, if not beyond, values documented in the literature (Haeberli, 2016), and which - if generally applied - would produce total regional glacier volumes in excess by about 25 – 40% of other estimates (cf. model inter-comparisons by Farinotti et al., 2017). However, modelled ice thickness with *GlabTop* is dependent mainly on surface slope. If glacier surface slope is smooth and regular as at the bedrock step at the long profile 1 at Argentière glacier, the ice thickness is smooth and regular as the surface and there is no GBO. The principal source of such uncertainties related to numerical model calculation is the difficulty with realistically parameterizing mass fluxes at the surface (mass/energy balance), within (ice deformation) and at the base of the ice (sliding, subglacial sediment deformation) in numerical model approaches. These aspects are fundamental and still unsolved problems in modern glaciological research, which cannot easily be overcome. Moreover, the assumption that glacier surface topography in some way reflects glacier-bed topography is a reasonable but not safely and quantitatively proven concept. Digital terrain models “without glaciers” based on modeled ice thicknesses therefore remain first-order approximations of future surface topography after de-glaciation. Using multiple model applications (Farinotti et al., 2019) together with continuous adjustments through focused field measurements (drillings, geophysical soundings) and monitored changes in glacier margins and exposed terrain are necessary to upgrade and continuously update this first-order information.

In contrast to absolute values of ice thickness and bed topography, glacier-bed topology (spatial neighborhood relations) is more directly influenced by the spatial patterns of surface slope. Modeling and mapping of GBOs as a classical example of glacier-bed topology analysis may therefore be considered to be more reliable, and the location of potential future lakes has been demonstrated to be quite robust in our study in that they quite safely indicate “that” and “where” flat to over-deepened bed parts exist beneath still existing glaciers (cf. 4.2.2). Nevertheless, it has to be kept in mind that the predicted geometries of the GBOs constitute very rough estimates only. Therefore, further quantitative analysis using modeled GBOs geometrical parameters (e.g. simulating peak discharge during GLOFs using volumes from model predictions) involve large uncertainties. Indeed, these predictions face difficult problems caused by adverse slopes at bedrock thresholds such as correct model representation of longitudinal stress coupling in glacier flow (Adhikari and Marshall, 2013) or of spatial variability in sub-glacial water pressure and basal sliding. Furthermore, all possible transitions from strikingly clear over-deepened structures with steep adverse slopes (cf. figure 7 in Haeberli et al., 2016b) to weakly pronounced forms and flat but smooth terrain exist in nature. An important possibility to reduce or at least differentiate the resulting limitations and uncertainties affecting quantitative approaches is to apply systematic classification steps based on qualitative assumptions and integrative expert knowledge about morphological surface characteristics as related to the physical processes of glacier flow through over-deepened terrain with adverse slopes (Frey et al., 2010). It is this integrative expert knowledge, which allows defining different confidence levels and correspondingly differentiated interpretations.

A special problem concerns heavily debris-covered glaciers where assumptions about near-equilibrium conditions or constant basal shear stresses may be especially unrealistic under conditions of continued warming. Such glaciers are becoming more and more important in the MBM (*e.g.* Miage or Talèfre glaciers). Under the influence of heavy sediment input from surrounding rock walls, debris-covered glaciers tend to have sediment rather than rock beds (Zemp et al., 2005). Even really existing GBOs becoming exposed in such cases may not yield lakes or only temporary ones because of highly permeable non-consolidated material. Over time, siltation at lake bottoms can lead to a reduction in permeability and corresponding prolongation of lake existence (cf. Haeberli et al., 2001). In this context, the determination of an erosion/sedimentation index as proposed by Zemp et al. (2005) could help with anticipating where in the future thick moraine beds, bare rock beds or mixed moraine/rock beds will most likely become exposed. Lake formation in exposed GBOs of rock beds may also be limited or even suppressed in cases by the existence of deeply-cut narrow, gorge-like outflow channels (*e.g.* Fig. 10) which cannot be predicted at present by any model calculation. Independently of sediment or rock beds, lakes forming in exposed GBOs can slowly or quickly become filled with sediments. Rough estimates of resulting lake-lifetimes can be made by applying realistic average erosion rates (for instance about 0-1 mm per year in glacier-covered parts and 1 – 10 mm per year in ice-free peri-/paraglacial parts of the respective catchments (Hallet et al., 1996; Hinderer, 2001; Fischer et al., 2012a; cf. discussion in Linsbauer et al., 2016)). This could help with order-of-magnitude guesses. Repeated lake bathymetries would then enable refining such first guesses for individual lakes which have come into existence.

The likely timing of future lake formation has only very roughly/empirically been estimated. Refinements are possible with the application of numerical glacier models. As the retreat of glacier margins can at least temporarily be influenced by the formation of lakes, this effect should be included in models of future glacier evolution. In addition, glacier retreat is by essence nonlinear, with usually enhanced retreat at very steep parts where the ice is rather thin, which can result in glacier tongue detachment (*e.g.* Vincent et al., 2019), or narrowing such as at the Bossons glacier (sect. 4. 2. 3). Nevertheless, the present regional assessment helps finding potential hot spots as locations of potential future risks and/or resource areas, but more detailed local investigations would be relevant in order to refine estimations of the potential lake characteristics (geometry, damming material, possible infill) and timing.

5.3. A view to the future applications

The resulting knowledge basis gained for estimating potential future lakes provides key-information for land-planners and policy-makers who have to deal with risk reduction, water resources for hydropower production or for water supply, as well as tourism and recreational activities under rapidly changing environmental conditions in high mountain regions (Haeberli et al., 2016a; Colonia et al., 2017; Drenkhan et al., 2018; 2019). With rapidly vanishing surface and subsurface ice, land-planning has to take into account environments which drastically change far beyond present-day conditions, causing strong and long-lasting disequilibria in complex interconnected geo- and ecosystems. Among the most prominent effects in rugged mountain topography are changes in slope stability and sediment cascades. Like in most other glacierized mountains on Earth, possible new lakes in the MBM will form in close proximity to sharp icy peaks with slowly degrading but also long-persisting permafrost and often in immediate neighborhood to over-steepened glacially de-buttressed slopes (Fig. 11). The frequency of large mass movements from warming icy peaks (Carey et al., 2012) or recently de-buttressed slopes (Hubbard et al., 2005; Kos et al., 2016) seems to be increasing (Coe et al., 2018; Deline et al., 2015, Fischer et al., 2012a, 2012b, Ravanel and Deline, 2011) and smaller rock-falls from perennially frozen slopes are particularly numerous during hot summers (Ravanel et al., 2017). The increasing probability must therefore be taken into account of extremely energetic mass movements (De Blasio et al., 2018) from steepest ice-clad frozen peaks or de-buttressed lateral slopes to reach new lakes and to trigger impact waves, which have the potential to transform into far-reaching floods and debris flows (Carey et al., 2012; Haeberli et al., 2017).

This hazard aspect also concerns new constructions for artificially dammed/controlled reservoirs at or near new lakes in connection with hydropower development or fresh-water supply (Farinotti et al. 2016; Terrier et al, 2011), which may best be combined with flood-protection concepts (Haeberli et al. 2016a). The numerous and potentially large lakes predicted all along the Argentière glacier could be examples of such combined considerations. The Mer de Glace, Argentière, Tour and Tré-la-Tête glacial water are already exploited by the *Electricité de France* and *Emossons* companies, either with sub-glacial or pro-glacial intakes. The lowest predicted GBO at the Tour glacier, the potentially large water bodies forming at the Tré la Tête, Triolet and Bionnassay glaciers, and those predicted at the Talèfre and Triolet glaciers could become future hot spots in terms of resources, especially because they do not seem to be directly threatened by high and destabilizing permafrost rock walls (Fig. 11 and 12). They could however become exposed to steep and close-by de-buttressed slopes. At the Bionnassay glacier, permafrost rock walls are not directly standing above the forming water body but higher up above the glacier across which flow velocity of potential rock-ice avalanches may be high enabling long run-out distances (*e.g.* Sosio et al., 2012; De Blasio, 2014).

In connection with such reflections about future options and risks, possible outbursts of sub-/englacial water pockets and the conditions/processes in pro-glacial torrents and rivers must also be considered. Outbursts of sub-/englacial water pockets have already happened. The most dramatic event occurred in 1892 when an englacial water pocket outburst from the Tête Rousse glacier (Fig. 12b) triggered a large debris flow devastating the village of Saint Gervais and causing 175 fatalities. (Vincent et al., 2010). Because of its narrowness and the related positioning of only one branch line *GlabTop* does not predict any GBO at this glacier, but two GBOs are identified from morphometric analysis with level of confidence $\geq$ 3, and are also visible on GPR data presented by Vincent al. (2010). In spite of decreasing pro-glacial stream activity since the end of the Little Ice Age (1850) in the Chamonix valley (Berthet, 2016), many debris flows have occurred throughout the 20th and into the 21st century, sometimes damaging infrastructure such as the Mont Blanc tunnel road (Fig. 12a). For the Dards, Favrands, Creusaz, Bossons, and Griaz streams, the outburst of intra-glacial water pockets has been reported for many events. For all these streams except the Griaz, potential GBOs where lakes already formed (Pèlerins glaciers) or could form in the future (Bossons glacier) may have been locations for sub-glacial water pockets (Cook and Swift, 2012), even though the relation between en- or subglacial water pockets and overdeepened glacier beds remains unclear. At the Griaz glacier, no potential GBOs was predicted or detected. This could well be due to the DEM spatial resolution which does not capture small areas such as the flat crevasse-free glacier surface between the two crevassed fields, which is about 60 m long and 300 m wide (Fig. 12c). Nevertheless, most criteria except the calculated slope angle are gathered for this site and suggest favorable conditions for GBOs existence and related water storage. Ice avalanches are also a recurrent hazard in the MBM (*e.g.* Vincent et al., 2015), and retreating glacier fronts in steep slopes overhanging potential future lakes such as at the Bossons glacier might become an emerging hazard source.

These preliminary reflections show the necessity to develop scenario-based integrative studies, taking into account current and future interactive processes (Allen et al., 2019), but also to consider past events to detect possible sites which are not highlighted by the inherently coarse approximation related to regional multi-criteria approaches (GAPHAZ, 2017). To better address possible resources and risks associated with potential future lakes, detailed analyses of the relevant lake characteristics (volume, surface area, etc.) and parameterized glacier retreat models would be relevant. Additionally, rock fall impact susceptibility into these lakes might be an important step to conduct at the regional scale for a first order estimate of potential hot spots in terms of risks (Schaub, 2015), and numerical model simulations taking cascading processes into account would be of high importance for assessing potential hazard zones (e.g. Somos-Valenzuela et al., 2016, Worni et al., 2014).

6. Conclusions

In this study, we predict and identify the potential of future lake formation at the regional scale of the Mont Blanc Massif, in order to achieve essential step towards an integrative approach of potential hazards and options resulting from de-glaciation processes. Our investigation leads to the following conclusions:

- About 80 glacier-bed overdeepenings (GBOs) may exist below the current glaciers and could give rise to future lake formation, the largest and most voluminous being located at the bottom of the Tré-la-Tête and Talèfre glaciers. This last one may however be smaller than expected from the prediction due to the presence of deeply incised gorges at its rock threshold (Fig. 10).

- Considering the comparison of the predicted GBOs with recently formed water bodies and measured bedrock topography, the location of the predicted GBO is rather robust while their depth and volume are highly uncertain and tend to be underestimated.
- Five water bodies have started to form within the past decade at GBOs predicted with the *GlabTop* model; 31 have a high level of confidence (4 to 5 of 5 morphological criteria fulfilled - 8 having 5/5), 23 reach 3/5 and 26 have a value of 2/5. This means that 1/3 to 2/3 of the analyzed GBOs likely exist and are possible locations for future lakes.
- Considering recent glacier retreat rates, only 2 potential lakes may start to form imminently (during the coming years), in addition to the 5 water bodies which have already started to form at the terminal ice margin and which were used for validating the location of the predicted GBOs.
- In addition, 3 to 6 other potential lakes could also start forming within the next decades under constant or accelerated glacier retreat rates; during the same time period 6 other lakes could also form on the southern side of the massif if glacier retreat accelerates by at least a factor of two as compared to the rate of 1970's-2000's.
- When considering a straightforward assessment of future glacier retreat, on-going lake formation and the level of confidence of the potential future lakes, the Tré-la-Tête, Bionnassay, Pèlerins, A Neuve, Triolet, and Talèfre glaciers will possibly yield new lakes in the coming decade. The potential lake at Pèlerin glacier remains uncertain due to the absence of consolidated damming material or an impermeable lake bed.
- Similarly, the Tour, Bossons, Argentière, Lée Blanche, Estelette and again the Triolet glaciers will possibly uncover overdeepenings and enable the formation of lakes before mid-century under constant or accelerated glacier retreat.
- In terms of possible risks of sudden water drainage, or impact waves caused by rock/ice avalanches or other mass movements. Notably high-energy rock/ice avalanches with extended trajectories on/across glaciers in the Pèlerins, Bossons, Bionnassay, or Talèfre catchments might become sources of high-magnitude events from over-steepened and increasingly de-buttressed slopes or from sharp icy peaks with degrading permafrost.

- Potential future lakes that could form in the coming decades may also become interesting as potential water storage for hydropower production and water supply but require careful assessment of related hazard and risk potentials.

Our study shows the potential of a semi-quantitative approach at the regional scale to identify potential future hot spots in terms of natural hazards and to guide detailed analysis at the site scale.

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Figures

Figure 1. Evolution of the Mer de Glace front between 1986 and 2016, with the highly debris-covered tongue, small lakes forming and in some cases filling up due to strong sediment input.

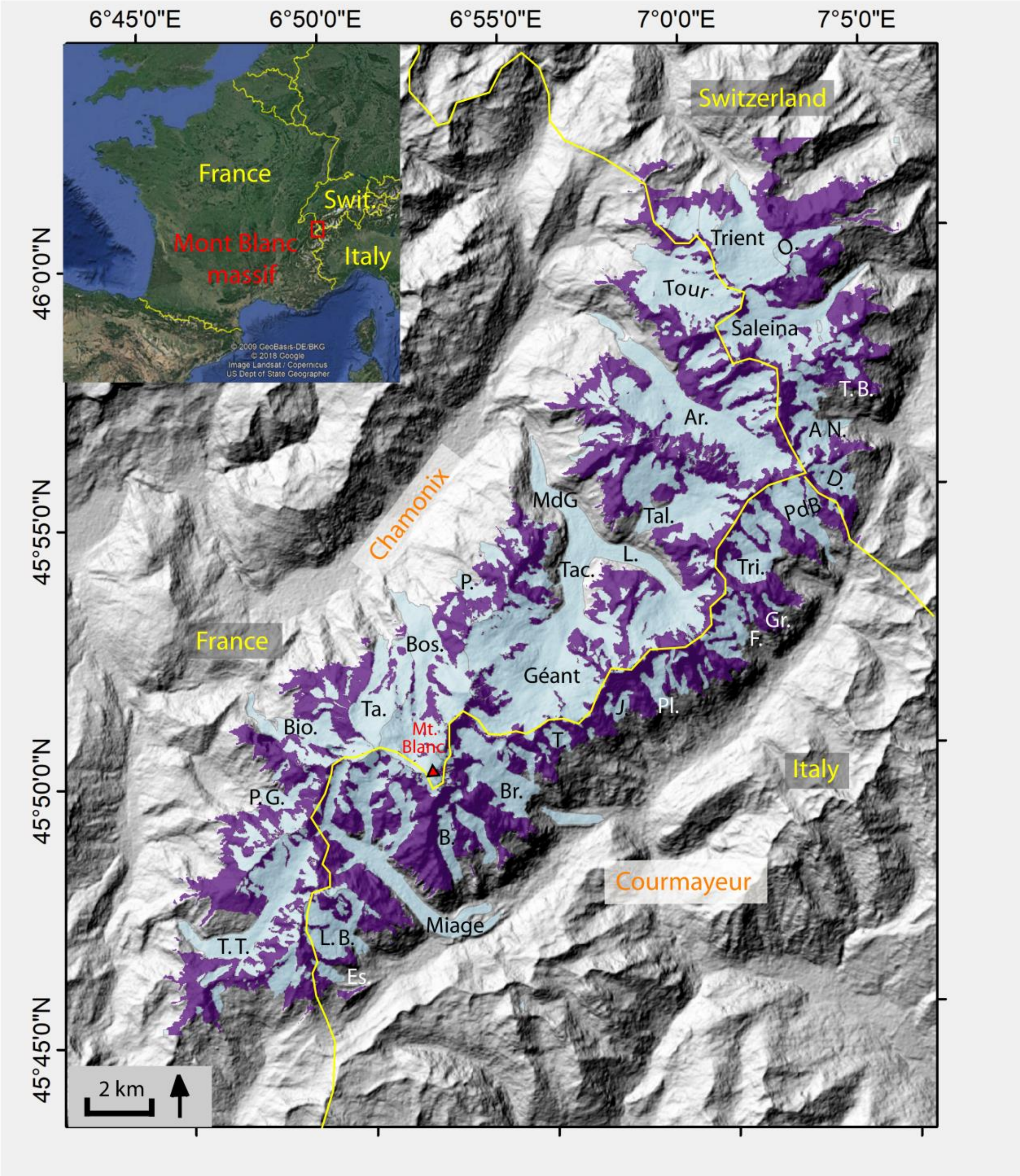


Figure 2. The Mont Blanc massif. Light blue areas are glaciers. Purple areas are permafrost areas (i.e. permafrost index > 0.5 after Marcer et al., 2017). **MdG:** *Mer de Glace*, **Tac.:** *Tacul glacier*, **G.:** *Géant glacier*, **Tal.:** *Talègre glacier*, **L.:** *Leschaux glacier*, **Ar.**: *Argentière glacier*, **Tri.:** *Triolet glacier*, **PdB:** *Pré de Bar glacier*., **D.:** *Dolent*, **A N.:** *A Neuve*, **O.:** *d'Orny glacier,* **P.:** *Pèlerins glacier*, **Ta.:** *Taconnaz glacier*, **Bos.:** *Bossons glacier*, **Bio.:** *Bionnassay glacier*, **P. G.:** *Plan Glacier*, **T. T.:** *Tré la Tête glacier*, **Es.:** *Estelette glacier*, **L. B.:** *Lée Blanche glacier*, **B.:** *Brouillard glacier*, **Br.:** *Brenva*

glacier, **T.:** *Toule glacier*, **J.:** *Jetoula glacier*, **Pl.:** *Planpincieux glacier*, **F.:** *Frebouze glacier*, **Gr.:**

1030 *Gruetta glacier*, **T. B.:** *Treutse Bô glacier*.

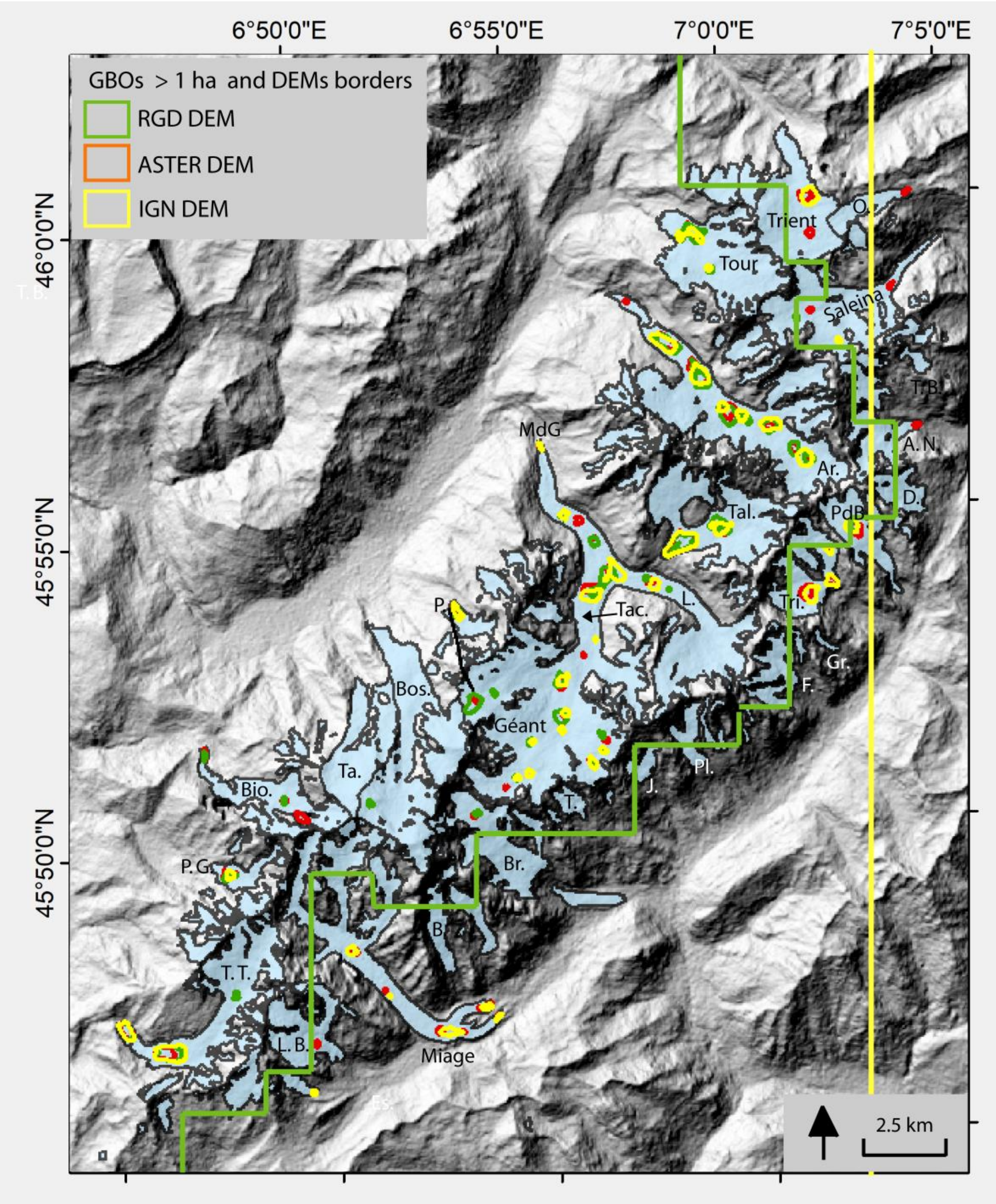


Figure 3. Predicted GBO with the 3 DEMs and their respective coverage. The yellow line represents the RGD DEM limit, the green line represents the eastern limit of the IGN DEM and the ASTER DEM covers the entire area. Details on the glacier acronyms are given in Figure 2.

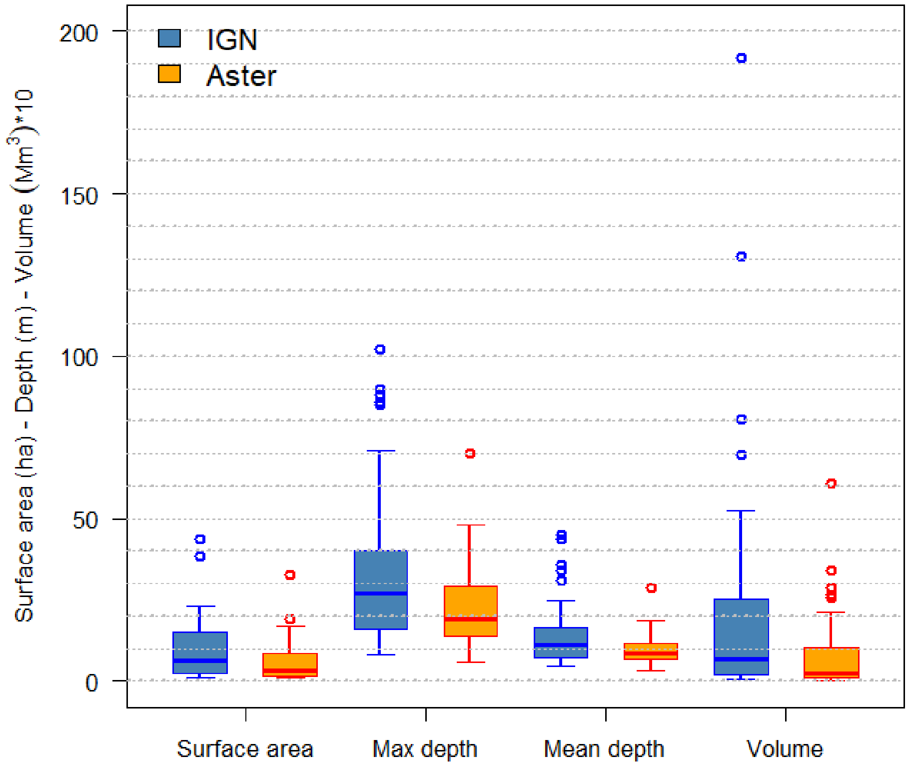


Figure 4. Morphological characteristics of the GBOs predicted with *GlabTop* based on the ASTER and the IGN DEMs. Given that the RGD DEM does not cover the Italian and Swiss side of the massif, results gained from this DEM are not comparable with those of the two other DEMs.

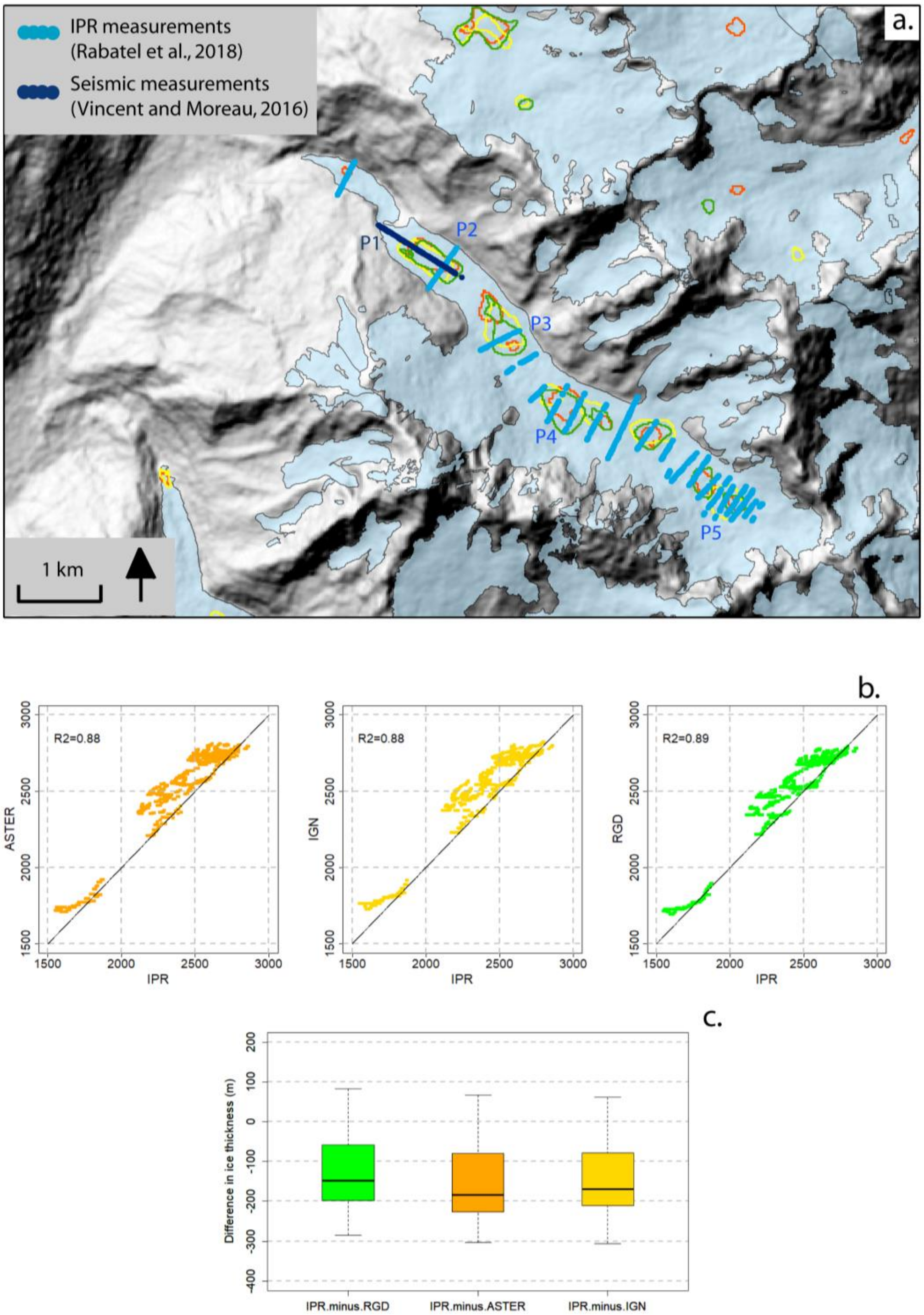


Figure 5. Evaluation of the *GlabTop* output with IPR measurements from Rabatel et al. (2018) on the Argentière glacier. **a.** Locations of the IPR measurement points. **b.** Scatter plots of glacier bed topography inferred from IPR measurements and predicted with *GlabTop*. **c.** Summary statistics of the differences between IPR measurements results and *GlabTop* output.

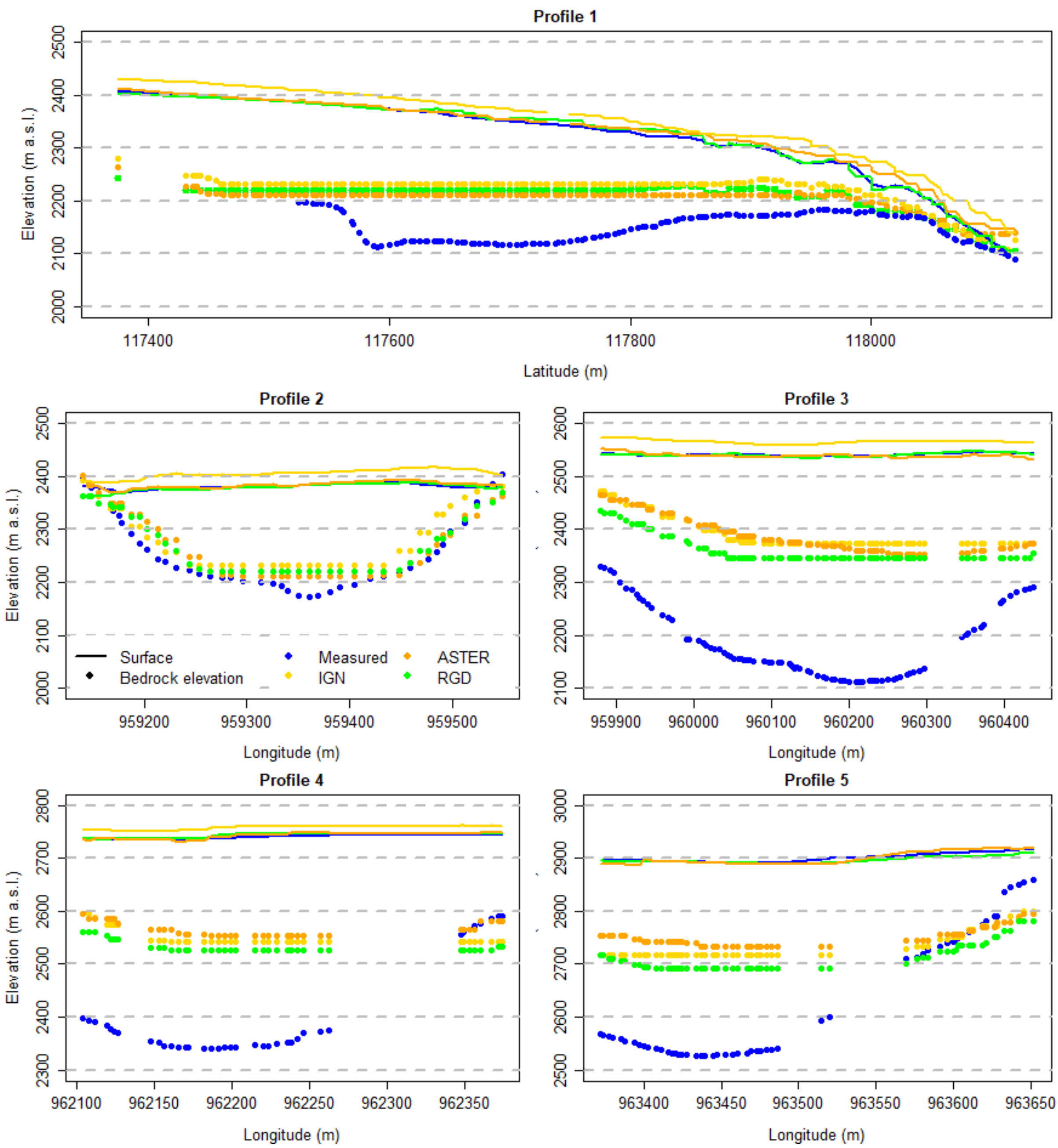


Figure 6. Shape of the glacier bed and glacier surface inferred from IPR measurement and *GlabTop* with the 3 DEMs. The "measured surface" is extracted from a photogrammetric DEM used for further analysis with the IPR measurements from Rabatel et al. (2018). The location of the profiles is visible on Figure 5: Profile 1 is lengthwise while the four other profiles are cross-sectional.

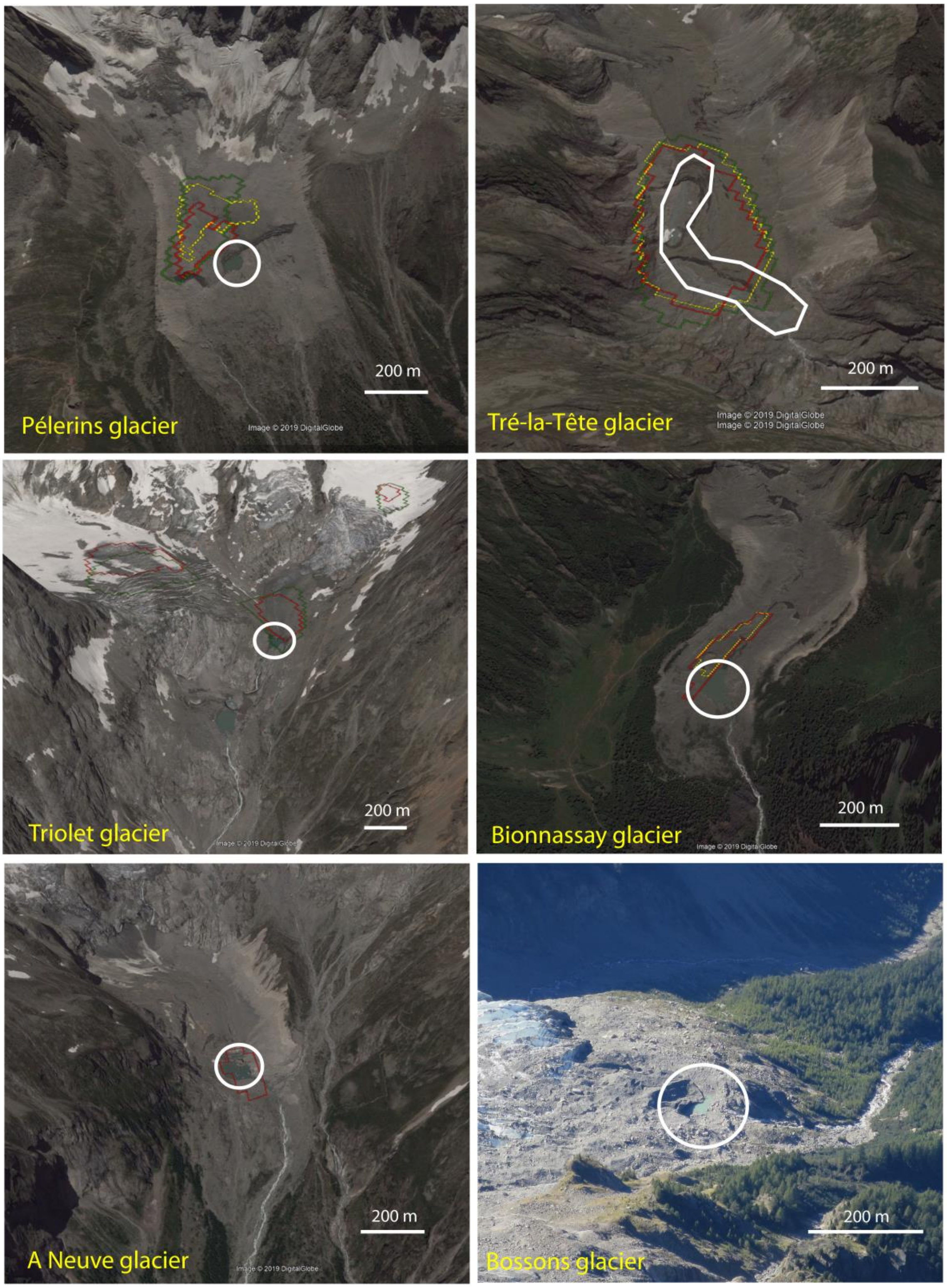


Figure 7. New lakes forming (white circles) at recently retreated glacier front or supra-glacial lakes at location of predicted GBOs. Images are from Google Earth, except for the Bossons glacier which is a picture from F. Magnin taken in September 2019

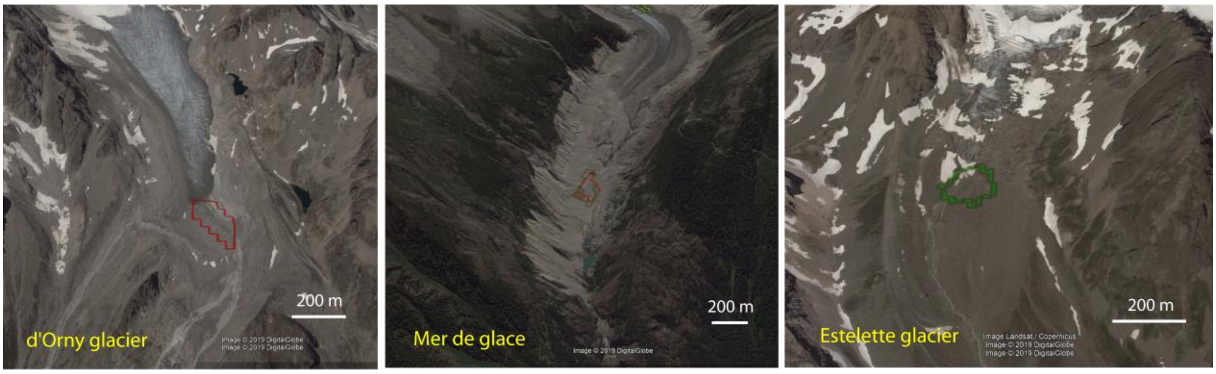


Figure 8. Absence of lakes at recently retreated glacier fronts at location of predicted GBOs.

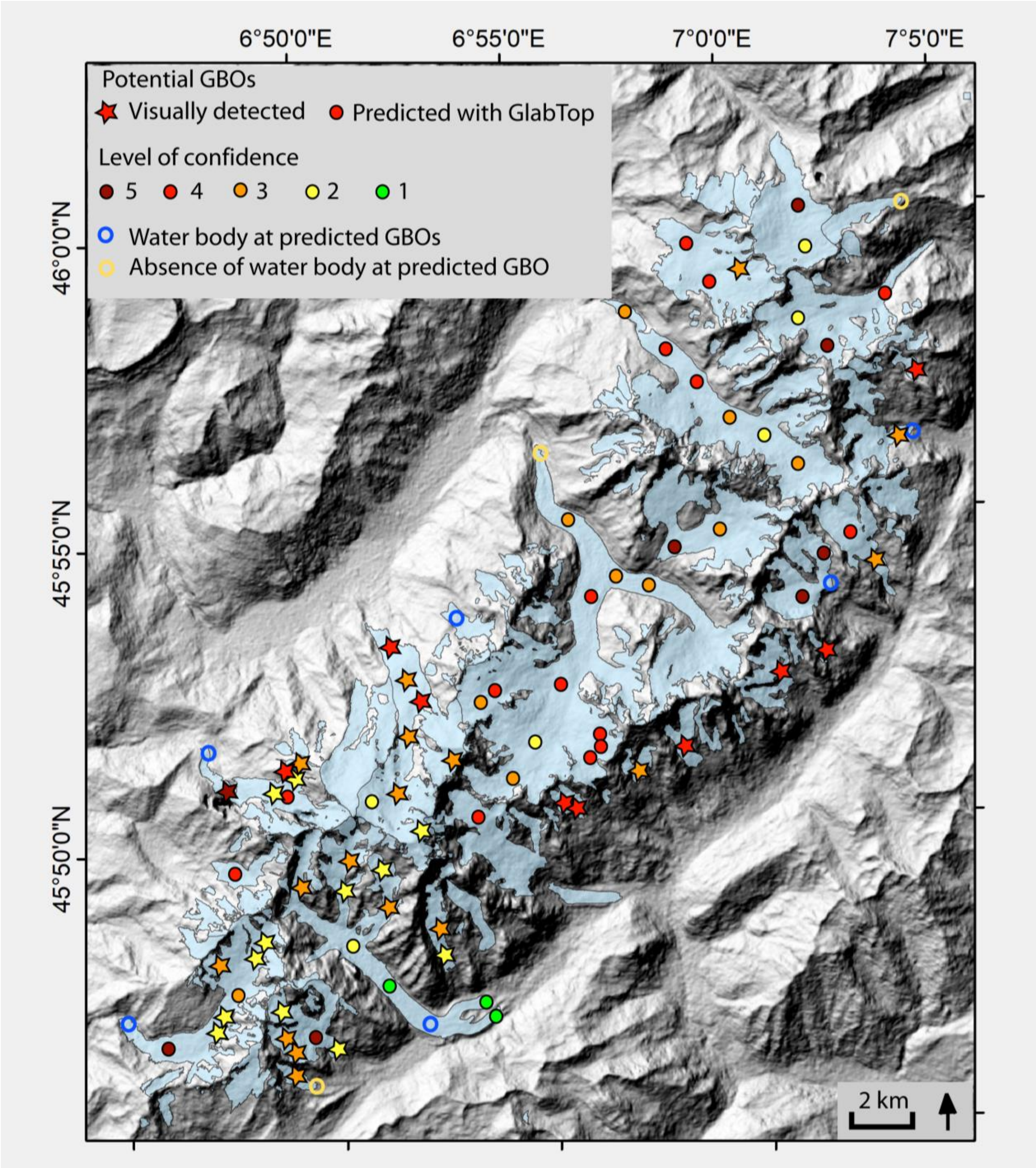
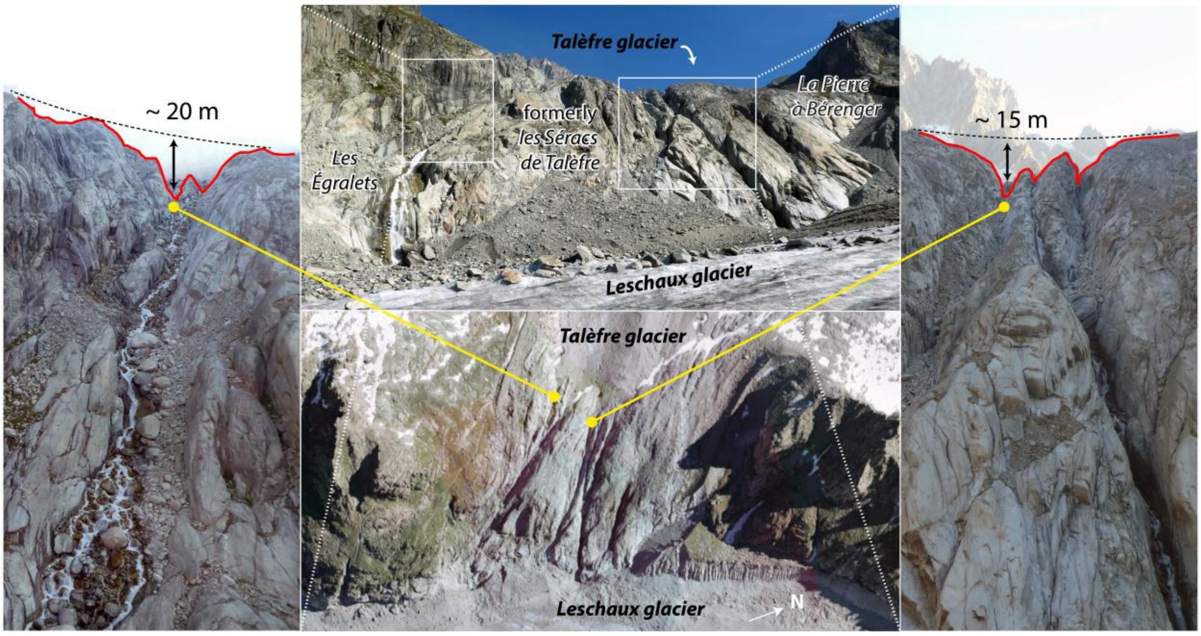


Figure 9. Location and level of confidence of the predicted GBOs and those detected by visual analysis.



1060 **Figure 10.** The Talèfre glacier and deep gorges in the downstream bedrock threshold.

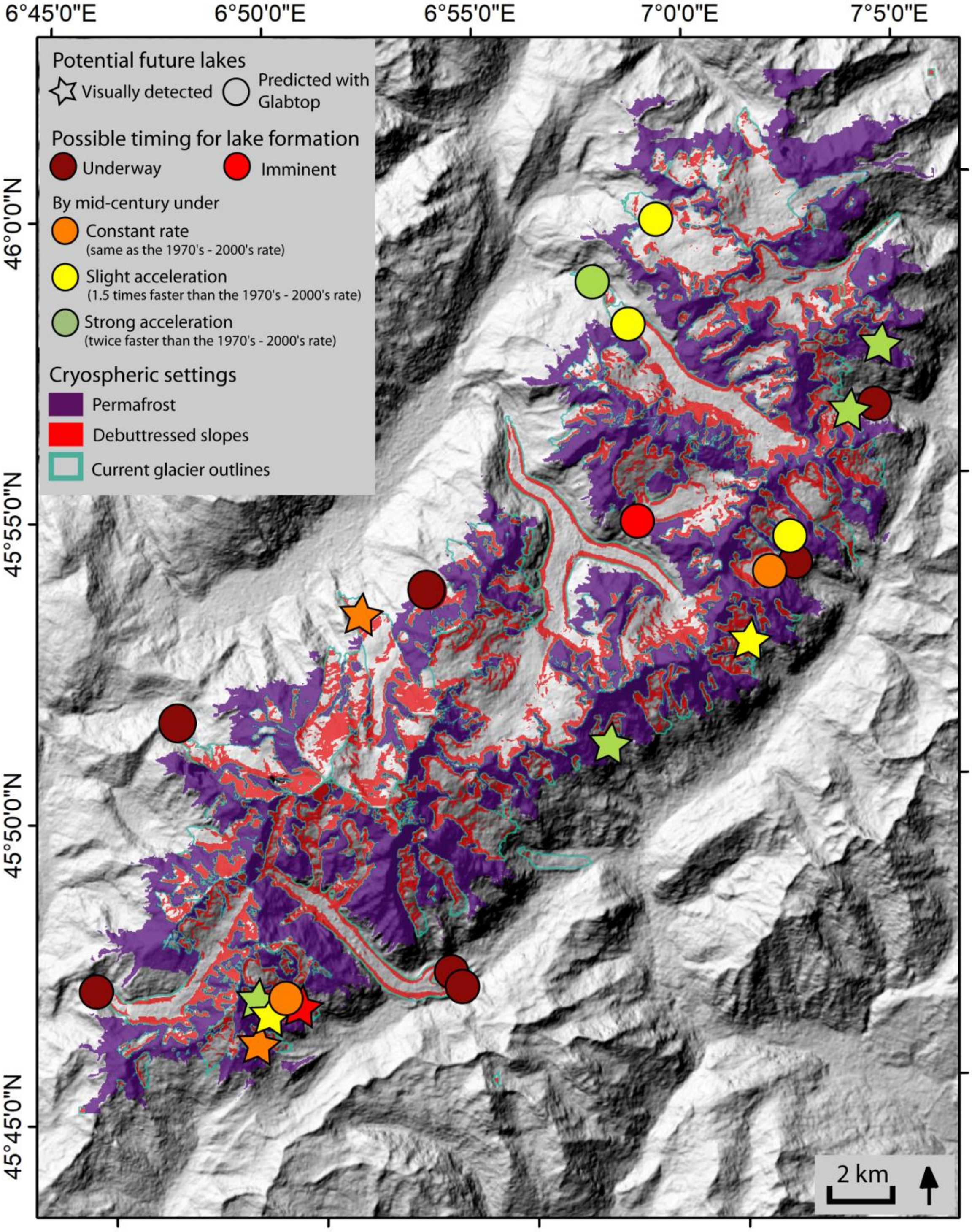


Figure 11. Timing of potential lake formation within the 21st century and possible hazards resulting of de-glaciating processes (permafrost degradation and glacier retreat). The de-buttressed steep slopes refer to slopes > 30° currently below the glacier surface.

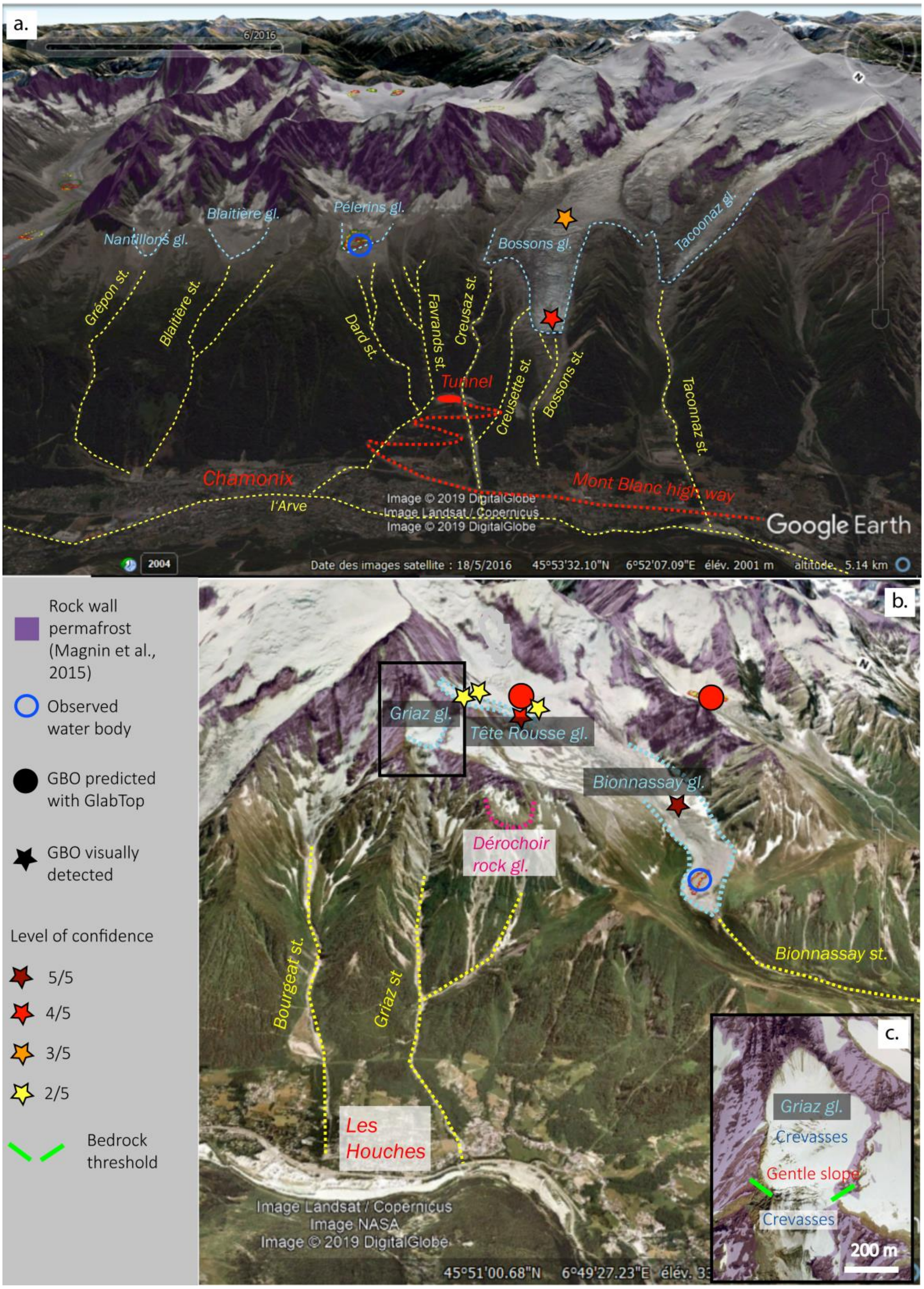


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Figure 12. Example of potential hot spots in terms of risks based on already known active pro-glacial stream systems. **a.** General view of the Northwest face of the MBM. **b.** Focus on the Griaz, Tête Rousse and Bionnassay glaciers and Les Houches village. **c.** Focus on the Griaz glacier.

Table list

Table 1. Details of the topographical and glacier inventory data used to run *GlabTop*. * The spatial coverage of the respective DEMs is visible in Figure 3.

Table 2. Summary of the morphological analysis and classification criteria to determine the level of confidence of predicted GBOs. * Less than 20 % of the glacier surface area above the predicted GBOs has a slope angle < to 20°. ** Less than 20 % of the downstream surface area has a slope angle change < 5°.

Table 3. Details of the glacier outline data used to reconstruct the glacier retreat rate since the 1970's.

Table 4. Summary statistics of the predicted GBOs with the ASTER and IGN DEMs. Statistics are not provided for the RGD DEM because it does not cover the Swiss and Italian sides of the massif. Statistics with the IGN are slightly biased because the IGN DEM does not cover the lowest part of the Swiss glaciers (see Fig. 3).

Table 5. Characteristics of the recently formed water bodies at predicted GBOs. * O.b = "out of DEM bound"; ** See Tab.2