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Modéliser les surcreusements sous glaciaires pour déterminer les futurs lacs potentiels dans les Alpes françaises

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Abstract

Glacier retreat results in major landscape changes including the formation of new lakes in Glacier-Bed Overdeepenings (GBOs) that can provoke catastrophic Glacial Lake Outburst Flood (GLOF) hazards, but could also provide economic opportunities. This study aimed to identify and characterize the location of potential GBOs in the French Alps as possible sites for future lakes. We first ran GlabTop (Glacier-bed Topography) and GlabTop 2 models, two GIS schemes calculating glacier ice thickness and mapping potential GBOs. Their level of confidence is estimated using morphological analysis based on slope angle, crevasse fields and lateral narrowing at bedrock thresholds. 139 GBOs (> 0.01 km²) were predicted among which 59 have medium to very high confidence. 19 lakes are already forming at the snout of retreating glaciers, including 2 lakes at predicted GBOs < 0,01km². The Vanoise massif hosts 43% of the predicted GBOs but the Mont Blanc massif gathers larger, deeper and more voluminous ones. Most of the predicted GBOs are below 3500 m a.s.l. and is related to that of glaciers. In the Vanoise massif, many predicted GBOs have rather low level of confidence because of the extent of ice-cap like glaciers for which the shear stress approach used by GlabTop becomes questionable. Furthermore, 58 potential GBOs were detected by visual analysis of glacier morphologies. The study highlights the relevance of combining various methods to determine GBOs and is a first step towards the anticipation of future risks and opportunities related to the formation of new lakes in the French Alps.

Résumé

Dans le contexte actuel de retrait glaciaire, les paysages laissent parfois place à la formation de nouveaux lacs dans les surcreusements des lits glaciaires. Ces lacs peuvent constituer ou amplifier des aléas naturels (e.g. vidange brutale d'un lac) ou être source d'opportunités économiques. Cette étude vise à identifier et caractériser les surcreusements sous glaciaires pour déterminer les futurs lacs potentiels dans les Alpes françaises. La topographie sous glaciaire est modélisée grâce aux modèles GlabTop (Glacier-bed Topography) et GlabTop 2 qui calculent l'épaisseur des glaciers et cartographient les surcreusements potentiels. Le niveau de confiance des surcreusements est estimé en analysant la morphologie des glaciers (i.e. angle de pente, crevasses, présence/absence de verrou rocheux). 139 GBO ($> 0,01$ km^2) ont été détectés, dont 59 qui ont un niveau de confiance moyen à très élevé. L'approche utilisée n'est pas adaptée aux calottes glaciaires, ce qui explique certains faibles niveaux de confiance en Vanoise. 19 lacs se forment déjà au front de certains glaciers, dont 2 dans des surcreusements $< 0,01$km^2. 43% des surcreusements détectés sont en Vanoise, mais le massif du Mont Blanc rassemble les plus grands, les plus profonds et les plus volumineux. La majorité des surcreusements sont en dessous de 3500 m d'altitude. 58 surcreusements potentiels ont également été détectés en analysant visuellement la morphologie des glaciers. L'étude souligne la pertinence de combiner différentes méthodes pour détecter les surcreusements et constitue une étape clé vers l'anticipation des risques et opportunités liés à la formation de nouveaux lacs dans les Alpes françaises.

Keywords

Deglaciating landscapes, Glacier Bed Overdeepenings, potential future lakes, French Alps, hazards anticipation

Mots clés

Déglaciation, surcreusements glaciaires, futurs lacs potentiels, Alpes françaises, anticipation des aléas naturels.

1. Introduction

Global warming is particularly pronounced in high mountain environments and has accelerated in the past decades (IPCC, 2019). In the French Alps, air temperature has increased by +1.5 °C to +2.1 °C since 1950 (Einhorn et al., 2015). This has strong impacts on the Alpine cryosphere, such as rising of the rain-snow limit by about 400 m since the 1980s (Böhm et al., 2010), permafrost degradation (Magnin et al., 2017; PERMOS, 2019) and glacier retreat (Zemp et al., 2015). In the European Alps, glacier surface area has decreased by 50% and lost 200 km^3 between the end of the Little Ice Age (LIA, 1850) and 2000 (Zemp et al., 2006). This trend has clearly accelerated in the recent decades (Huss, 2012; Zekollari et al., 2019).

The ongoing deglaciation results in an extension of periglacial environments and sometimes of new lakes forming in glacier bed overdeepenings (GBO). These lakes are by essence located in unstable and transient environments. They could be a source of natural hazards related to Glacial Lake Outburst Floods (GLOF) that could be provoked by sudden dam break or by displacement waves triggered by mass movements (Allen et al., 2016b; Ashraf et al., 2012; Clague and Evans, 2000; Emmer, 2017; Hubbard et al., 2005). Glacial lakes are sometimes located near potentially unstable slopes subject to debuttressing and/or permafrost degradation and can amplify gravitational hazards such as rock avalanches (Haeberli et al., 2017) provoking chains of processes that can travel over long distances and reach valley floors (Byers et al., 2018 ; Walter et al., 2020). When such far-reaching cascading processes happen in densely populated valleys, the socio-economic impacts can be dramatic (Carey, 2005, 2012).

Beyond the threat, those new water bodies can also be an opportunity for hydroelectricity production with the creation of hydraulic dams (Haeberli et al., 2016), or through their attractiveness for tourists (Purdie et al., 2013).

Nevertheless, GBOs not always turn into perennial lakes as they are sometimes filled with sediments, or they can drain when lakes form in permeable morainic material (Haeberli et al., 2001). In the French Alps, this was for example the case at the front of the emblematic Mer de Glace (Mont Blanc massif) where a lake was present in the 1990s but was progressively filled with sediments (Deline et al. 2012; Magnin et al., 2020) or at the snout of Pèlerins glacier where a lake formed in 2015 but drained in 2016 (Magnin et al., 2020).

Recently developed models, based on variable physical simplifications and input data are able to calculate spatially distributed ice thicknesses (Farinotti et al., 2009) and the resulting sub-glacial topography, revealing the location of potential GBOs in which lakes could form (Linsbauer et al., 2009, 2012; Paul and Linsbauer, 2012). Such studies have already been conducted in various mountain ranges such as, for instance, the Himalayas (Linsbauer et al., 2016), in Peruvian Andes (Colonia et al. 2015; Drenkhan et al., 2018), Central Asia (Kapitsa et al., 2017) and in Switzerland (Linsbauer et al., 2012). They are a necessary first step towards assessing GLOFs hazards and their impacts (GAPHAZ, 2017) and integrative modelling of future landscapes in glacial and periglacial areas (Haeberli, 2017). In the French Alps, potential future lakes have so far been investigated in the Mont Blanc massif (Magnin et al., 2020).

This work aims at extending the latter study to the entire French Alps in order to provide relevant baseline to anticipate risks and opportunities associated with future lake formation in presently still glacier-covered areas. To do so, we ran GlabTop (Glacier-bed Topography) and GlabTop 2 models, two GIS schemes calculating ice thicknesses from surface slope via basal shear stresses, with a different level of automation, and which both provide a map and morphometrics of potential GBOs. This method is combined with a visual analysis based on morphological criteria proposed by Frey et al. (2010), which helps in determining the level of confidence for each modelled GBO. In addition, the results of the simulations are evaluated by comparing predicted GBOs with lakes that newly formed or did not form in recently deglaciated areas. The results finally point to potential "hot spots" that could be more closely investigated in the future in order to assess related hazards, risks and opportunities.

2. The French Alps, a deglaciating mountain range

The French Alps are the western edge of the European Alpine arc and extend from the Mont Blanc massif in the north to the Mercantour adjoining the Mediterranean Sea in the south. With the Pyrenees, it is one of the two, but also the most glacierized mountain range in the mainland of France. According to the inventory by Gardent et al., 581 glaciers were counted in 2006/2009, covering 275,4 km² The smallest is a glacieret in the Ecrins massif (Bans glacier – 0.0015 km²) and the largest is the Mer de Glace in the Mont Blanc massif (30.5 km²). They are mostly located in the three highest-elevated massifs: Mont Blanc (83 glaciers), Vanoise (174) and Ecrins massifs (282). Some small glaciers also exist in the Belledonnes, Grandes Rousses and Ubaye massifs (fig. 1), while only glacierets persist in the Mercantour.

The mean altitude at which glaciers terminate in the French Alps is 2840 m a.s.l. The lowest altitudes are reached by glaciers of the Mont Blanc massif: the Bossons glacier (1429 m a.s.l.), the Mer de Glace (1531 m a.s.l.) and the Argentière glacier (1590 m a.s.l.). In the Ecrins and Vanoise massifs, the lowest frontal altitudes are reached by debris-covered glaciers: respectively the Noir glacier (2174 m a.s.l.) and the Pramort glacier (2325 m a.s.l.).

According to Gardent et al. (2014), glaciers have lost about half of their surface area between the end of the LIA and the 2006/2009 period in the Ecrins, Vanoise and Mont Blanc massifs. These authors also explain that glacier recession was 2.5 times faster between the 1967-1971 and 2006-2009 periods than between the end of the LIA and 1967-1971, with a decrease in glacier surface area of about 25% over the more recent period. Due to glacier retreat, Gardent (2014) inventoried 443 new ponds and lakes in proglacial areas since the LIA, of which 227 are over 500 m². Of these larger water bodies, 14 are located behind potentially unstable dams consisting of non-consolidated morainic material).

Fig. 1 – Location map: The French Alps and their main ice-covered massifs. (Coordinate system : WGS84).

Fig. 1 – Carte de localisation : Les Alpes françaises et leur massifs englacés. (Système de coordonnées : WGS84).

By the end of the 21st century, Alpine glaciers are expected to lose about 75% to 95% of their volume, depending on greenhouse gas emissions scenarios (Zekollari et al., 2019). In France, detailed projections have been proposed for only two of the largest glaciers: the Argentière and the Mer de Glace in the Mont Blanc massif (Vincent et al., 2019). This study suggests that these glaciers are likely to almost completely disappear before 2100 in the case of the most pessimistic scenario (RCP 8.5), and that the latter would be reduced to about 20% of its current surface area in a more optimistic scenario (RCP4.5). No detailed glacier retreat projection has so far been conducted at the scale of the entire French Alps. However, the glacier inventory provided by Gardent et al. (2014) offers the opportunity to predict possible locations of potential GBOs with the GlabTop model (Linsbauer et al., 2012).

3. Methods and data

The approach for determining GBOs as possible future lake locations in the French Alps is conducted by first running GlabTop and GlabTop 2 models, which use the same basic assumptions but differ by their level of automation. Then, after comparing and compiling results of both models, a morphological analysis is conducted on each predicted GBO to evaluate the level of confidence attributed to the prediction. We also evaluate the predictions by comparing recently formed water bodies and locations of simulated GBOs. Finally, we complete our investigation with a visual analysis of potential GBOs that would possibly have been overlooked by GlabTop approaches.

3.1. Modelling GBOs with GlabTop and GlabTop 2

The original GlabTop model is a GIS scheme which determines glacier bed topography using glacier outlines, a Digital Elevation Model (DEM) and manually drawn glacier branch lines (Linsbauer et al., 2009, Paul and Linsbauer, 2012). It calculates the ice thickness from surface slope at points sampled from the digitalized branch lines, assuming a relation between the basal shear stress and glacier elevation range as a governing factor of mass turn-over. Then, the ice thickness is subtracted from the original DEM to product a new DEM without glaciers. On this latter DEM, GBOs are delineated by GlabTop and can be interpreted as places for potential futures lakes.

GlabTop 2 runs on the same principles but is more appropriate to be applied over large areas as it is fully automatized and does not require manually digitized branch lines on each glacier. Thus, ice thickness is not derived along branch lines but is estimated by the average slope of all gridcells within a certain buffer on each glacier (Frey and al., 2014, Linsbauer and al., 2016). GlabTop2 GBOs are delineated based on modelled ice thickness according to the same procedure as with GlabTop.

We run GlabTop and GlabTOP 2 with the 25 m resolution DEM of the French Institute for Geography (IGN), the data basis of which was acquired between 2000 and 2010. As GlabTop2 performs reliable on a DEM resolution between 50 to 100 m, we resampled the input DEM to 50 m resolution. Glacier outlines were the ones from Gardent et al. (2014) drawn from orthorectified photographs taken between 2004 and 2009. Those are not the most updated contour lines, but they have the advantage to cover recently deglaciated forefield areas where lakes may, or may not, have formed and could be compared with predicted GBOs (sect. 3.2). Furthermore, the outlines (2004-2009) fit with the DEM (2000-2010), which is also important point for GlabTop modelling. To run GlabTop, branch lines were manually digitized on each glacier following advices from Paul and Linsbauer (2012), that is from bottom to top and perpendicularly to the contour lines of surface elevation. Each branch line ends about 100 m from the glacier outline and branch lines have a width interval of 200 m to 400 m.

To analyse the model results, the outputs of GlabTop and GlabTop 2 are combined. Where GBOs are predicted with both models, those from GlabTop 2 are removed. The morphometric characterization of predicted GBOs is thus mostly based on those predicted with GlabTop, but in most cases, the location is confirmed with GlabTop2.

3.2. Evaluation of GlabTop results

An evaluation of the results was conducted by comparing predicted GBOs with the presence or absence of lakes in most recently deglaciated areas. As GlabTop was applied to glacier outlines collected between 2004 and 2009, it is now possible to use more recent images available on Google Earth to determine whether lakes have formed or not where GBOS had been predicted. Magnin et al. (2020) already carried out such an analysis for the Mont Blanc massif, showing that water bodies have formed in 5 out of the 8 predicted GBOs at retreating glacier margins. In this study, we extend these results to the entire French Alps.

3.3. Determining the level of confidence for the predicted GBOs

To determine the level of confidence for each predicted GBO, a morphological analysis based on four criteria defined by Frey et al. (2010) is conducted. This analysis uses Google Earth images and considers (i) the slope angle at predicted GBO, (ii) the presence/absence of a break in slope angle downstream of the predicted GBO, (iii) the presence/absence of a bedrock threshold and/or a glacier narrowing at the predicted GBO outlet, and (iv) the presence/absence of a transition between a crevasse-free area and a crevasse field which indicates a transition from compressing to extending ice flow downstream of the predicted GBOs. For each criterion, a value ranging from 0 to 5 is attributed according to its obviousness (tab. 1). The sum of each criterion value is then calculated for each GBO, which can reach a maximum of 20 (four times 5), similar to Magnin et al. (2020).

Table 1 – Morphological analysis criteria used to determine the level of confidence for the predicted GBOs, following the approach proposed by Magnin et al. (2020).

Table 1 – Les critères de l'analyse morphologique utilisée pour déterminer le niveau de confiance des surcreusements glaciaires prédits, d'après l'approche proposée par Magnin et al. (2020).

When one of the criteria cannot be analysed (such as the transition between crevasse-free area and crevasse field in the case of debris covered glaciers) the total value cannot exceed 15. Then, a percentage of cumulated values relative to the maximum total value is calculated as follow:

- $(\sum 3 \text{ criteria}) / 15 \times 100$

- (∑ 4 criteria) /20 × 100

The third and final step consists in determining a level of confidence from 0 to 5 for each GBO which was defined according to the percentage of cumulated values as follow:

- < 10% = extremly low confidence (0/5)
- ≥ 10% < 30% = very low confidence (1/5)
- ≥ 30% < 50% = low confidence (2/5)
- ≥ 50% <70 % = medium confidence (3/5)
- ≥ 70% < 90% = high confidence (4/5)
- ≥ 90% = very high confidence (5/5)

This classification is largely based on subjective and qualitative assertions but involves integrative expert judgements related to the basic physics of glacier flow through overdeepened parts of their beds. It represents a strong and independent possibility to assess the degree of uncertainty and confidence with respect to GBOs predicted using numerical model calculations.

3.4. Visual identification of other potentials GBOs.

Some potential GBOs are not detected by the models, possibly due to the lack of accuracy or precision of the GlabTop input data, notably the DEM, which can smooth the topography and prevent the model from detecting possible breaks in slope angle (Magnin et al., 2020). Furthermore, the GlabTop model does not consider erosion-resistant bedrock ridges on lateral slopes and corresponding width-reduction of glacier flow, or spatial patterns of crevasse occurrences which are all important criteria defining potential GBOs. Glacier tongues can also be a limit in GBO-prediction where glacier outlines and DEM do not correspond in detail.

In order to complete the results of GlabTop and GlabTop 2 and to compensate the model limits, an additional analysis was performed by visually detecting potential GBOs based on transition from flat to steep glacier surface (criteria (i) and (ii)). In the same way as the predicted GBOs, the levels of confidence of those visually detected have also been determined by considering the other criteria. More specifically, a potential GBO is first detected at places where the criteria related to slope angles (i) and (ii) are ≥ 3 as proposed in Magnin et al. (2020), and then the presence/absence of crevasse fields and bedrock threshold is also analysed to classify the GBOs visually detected according to their level of confidence.

4. Results

Here we present the GBOs predicted by GlabTop, their main characteristics (localisation, surface area, depth, volumes, altitude) and the classification of GBOs likelihood by morphological analysis. We also evaluate the predicted GBOs comparing GlabTop outputs with water bodies in recently deglaciated ice-marginal areas. Finally, we complete the GlabTop result detecting other potential GBOs by a glacier morphological analysis.

4.1. Characteristics of the predicted GBOs

4.1.1. General features and data sorting

Predicted GBOs with GlabTop and GlabTop2 have similar locations (fig. 2).

Fig. 1 – GBOs predicted with GlabTop (yellow lines) and GlabTop 2 (orange lines).
Fig. 2 – Surcreusements sous glaciaires prédits par GlabTop (lignes jaune) et GlabTop 2 (lignes orange).
A: Mont Blanc massif; B: Ecrins massif; C: Vanoise massif; D: Grandes Rousses massif; E: Ubaye massif. (Coordinate system : Lambert 93 / RGF 93).
A : massif du Mont Blanc ; B : massif des Ecrins ; C : massif de la Vanoise ; D : massif des Grandes Rousses ; E : massif de l'Ubaye. (Système de coordonnées : Lambert 93 / RGF 93).
(MdG: Mer de Glace; Pel.: Pèlerins glacier; L.: Leschaux glacier; Bos.: Bossons glacier; Tac.: Taconnaz glacier; Bio.: Bionnassay glacier; T.T.: Tré la Tête Glacier; Inv.: Invernet glacier; l'Ar.: l'Argentière glacier; Gur.: Gurraz glacier; Fd.: Fond glacier; Sas.: Sassière glacier; R.G.: Rhêmes Golette glacier; Pra.: Pramort glacier; GM.: Grande Motte glacier; Ros.: Rosolin glacier; Ep.: Epéna glacier; Arc.: Arcelin glacier; Mar.: Grand Marchet glacier; Geb.: Gebroulaz glacier; Chav.: Chavière glacier; Pis.: Pisaillas glacier; Mo.: Montet glacier; Gef.: Géfret glacier; M.M.: Méan Martin glacier; Vlnt.: Vallonnet glacier; Va.I.: Vallonnet Inférieur glacier; Va.S.: Vallonnet Supérieur glacier; SdA.: Sources de l'Arc glacier; Mul.: Mulinet glacier; G.M.: Grand Méan glacier; Son.: Sonailles; Evet.: Evettes glacier; G.F.: Grand Fond glacier; Mic.: Roche Michel glacier; Bao.: Baounet glacier; Mel.: Rochemelon glacier; Som.: Sommellier glacier; Mt.L.: Mont de Lans glacier; Gir.: Girose glacier; Rat.: Rateau glacier; PdA.: Plate des Agneaux glacier; B.P.: Bonne Pierre glacier; VdE: Vallon des Etages glacier; Char.: Chardon glacier; S.W.: Sellettes glacier West; S.E.: Sellettes glacier East; Pil.: Pilatte glacier; Cond.: Condamines glacier; Bar.: Barbarate glacier).

However, GlabTop 2 predicts more GBOs than GlabTop, notably at the snout of narrow glacier tongues (fig 3). This is most probably an effect of digitized branch lines in GlabTop.

Fig. 3 – Example where only GlabTop 2 predicts GBOs at the snout of narrow glacier tongues). (The red lines are the flowlines used for GlabTop among which ice thickness is calculated. The orange polygons are the predicted GBOs with GlabTop 2).

Fig. 3 – Exemple de lieux où seulement GlabTop 2 prédit un surcreusement sous glaciaire au front d'une langue glaciaire. *(Les lignes rouges sont les lignes de flux utilisées par GlabTop pour calculer l'épaisseur de Glace. Les polygones orange sont les surcreusements sous glaciaires prédits par GlabTop 2).*

A: Chauvet glacier (Ubaye massif); B: Vallon des Etages glacier (Ecrins massif).

A : glacier de Chauvet (massif de l'Ubaye) ; B : glacier du Vallon des Etages (massif des Ecrins).

Part of the GBOs predicted with GlabTop2 have higher values for surface area and mean depth, resulting in correspondingly larger volumes (fig. 4; tab. 2). The third quartile of the surface area is at 0.11 km² with GlabTop and at 0.14 km² with GlabTop 2, and the third quartile of the mean depth is at 18 m with GlabTop and at 18.5 m with GlabTop 2. This explains the higher volumes with GlabTop 2 with a third quartile at 3.3 Mm^3 compared to GlabTop which the third quartile is at 1.7 Mm^3. However, the median values and most extreme outliers of these variables are slightly more important with GlabTop. The median value of the surface area is at 0.04 km² with GlabTop and 0.035 km² with GlabTop 2 while the ones of the maximum depth is 25 m with the former and 17.5 m with the latter. GlabTop also predicts greater maximum depth for more than half of the predicted GBOs, but the most extreme outliers of this variable are found with GlabTop2. Such differences are discussed in more details below (section 5.1).

Fig. 4 – Comparison of the surface area, max depth, mean depth, and volume of the GBOs between GlabTop and GlabTop 2.

Fig. 4 – Comparaison de la superficie, de la profondeur maximum et du volume des surcreusements sous glaciaires entre GlabTop et GlabTop 2

Predicted GBOs are most abundant in the Vanoise massif but the most extensive and most voluminous ones are found in the Mont Blanc massif (tab. 2). Maximum depths differ between the two GlabTop versions and from massif to massif. A maximum-depth value exceeding 100 m is produced by both model versions in the Mont Blanc massif, while in the Vanoise and Ecrins massifs it only results from GlabTop 2.

When analysing predicted GBO morphometrics in more detail, it has to be kept in mind that depths and volumes of GBOs tend to be generally underestimated (Magnin et al., 2020).

Nevertheless, those morphometrics can be used to compare GBOs with each other. In order to compare general GBO characteristics for different mountain ranges, we combine the outputs of GlabTop and GlabTop 2 and suppress duplicated GBOs at individual sites and keep only one per location. We thereby gave priority to the GlabTop output. A total of 139 GBOs (> 0.01 km^2) was finally found for the entire French Alps, including 40 GBOs in the Mont Blanc massif, 60 in the Vanoise, 30 in the Ecrins, 6 in the Grandes Rousses, 2 in the Ubaye and 1 in the Ruans massifs.

In the Mont Blanc massif, it is necessary to specify that when comparing our GlabTop outputs with those of Magnin et al., (2020), 6 GBOs were not identified by Magnin et al. (under the Tour, Bossons, Mer de glace, Géant and Bionassay glaciers), while 5 others had been predicted contrary to our previous results (under the Géant, Mer de Glace, Bossons and Bionassay glaciers). This could be explained by the different DEM and branch lines sets used in the two studies.

Table 2 – Comparison of the predicted GBOs characteristics with GlabTop (GT) and GlabTop 2 (GT2) for each massif of the French Alps.

Table 2 – Comparaison des surcreusements glaciaires prédits avec GlabTop (GT) et GlabTop 2 (GT2) pour chaque massif des Alpes françaises.

4.1.2. Surface areas of predicted GBOs

The predicted GBOs represent a total surface area of 9.48 km², about 3.5% of the glacier surface area. Half of it is in the Mont Blanc massif (4.81 km², 4.7% of the glacier surface area in the Mont Blanc massif), about 29% in the Vanoise massif (2.74 km², 3% of the glacier surface area in Vanoise massif) and 16% in the Ecrins massif (1.56 km², 2.3% of the glacier surface area in Ecrins massif; tab. 3).

Table 3 – Number and morphological characteristics of the predicted GBOs in each massifs of the French Alps when combining GlabTop and GlabTop 2 results and supressing the duplicated GBOs.

Table 3 – Nombre et caractéristiques morphologiques des surcreusements glaciaires prédits dans chaque massif des Alpes françaises, en combinant les résultats de GlabTop et GlabTop 2 et en supprimant les surcreusements en double.

The largest calculated GBOs, that are in the Mont Blanc massif (fig. 5), would be at the confluence of the Leschaux and Tacul glacier (top of the Mer de Glace), and at the Tré la Tête and Talèfre glaciers, with an area of 0.6 km², 0.52 km² and 0.47 km² respectively. In the Vanoise massif, the two GBOS that would have the largest surface area are under the Arcelin glacier (0.25 km²) and the Evettes glacier (0.21 km²). In the Ecrins massif, the two largest GBOs are both found under the Blanc glacier with a surface area of 0.23 km² and 0.22 km² respectively. Finally, another relatively large GBOs was predicted under the Saint Sorlin glacier with a surface area of 0.25 km² in the Grandes Rousses massif.

Fig. 5 – Comparison of the surface, volume and depth of the GBOs predicted by GlabTop between the Mont Blanc massif (MBM), the Vanoise massif and the Ecrins massif.

Fig. 5 – Comparaison de la superficie, du volume et de la profondeur des surcreusements sous glaciaires prédits par GlabTop entre le massif du Mont Blanc (MBM), la Vanoise et les Ecrins.

4.1.3. Depth of predicted GBOs

On average, the calculated GBOs are deeper in the Mont Blanc massif (fig. 5), and the deepest ones reach 146 m and 117 m respectively, and are both under the Argentière glacier. Another deep GBOs is found under Tré la Tête glacier (107 m).

In the Vanoise massif, the deepest GBOs are under Evettes glacier (75 m) and Rosolin glacier (65.5 m). In the Ecrins massif, the deepest GBOs are under the Noir glacier (47 m) and the Blanc glacier (45 m). Lastly, the GBO under the Saint Sorlin Glacier in the Grandes Rousses massif is deeper than the ones in the Ecrins an Vanoise with 81 m.

4.1.4. Volume of predicted GBOs

The total volume of the predicted GBOs is 217.4 Mm^3, 67% of which (145.5 Mm^3) is in the Mont Blanc massif, 19% (41.3 Mm^3) in the Vanoise massif and 9% (20.6 Mm^3) in the Ecrins massif (tab. 3). The GBOs with the higher volumes are mostly found in the Mont Blanc massif (fig. 5) such as those under the Talèfre glacier (24.8 Mm^3), the Tré la Tête glacier (22.4 Mm^3) and the Argentière glacier (20.7 Mm^3). In the same way as the surface area, the most voluminous GBOs in the Vanoise are those located under the Arcelin and Evette glacier (4.6 Mm^3 and 4.5 Mm^3 respectively). In the Ecrins massif, the most voluminous GBOs are under the Glacier Blanc (4 Mm^3) and the Arsine Glacier (3.3 Mm^3), and are both less voluminous than the one under the Saint Sorlin glacier (Grandes Rousses massif, 9 Mm^3).

4.1.5. Altitude of the predicted GBOs

The GBOs of the Vanoise massif are generally located at a higher altitude than in the other massifs, with a median value at 3000 m a.s.l., and many predicted GBOs are in the upper part of ice-cap shaped glaciers, such as the Pelve and the Arpon glaciers which have two GBOs at an altitude of 3491 m a.s.l. and 3475 m a.s.l. respectively. In the Ecrins massifs, GBOs are generally predicted at altitudes lower by 500 m, with a median value at 2500 m a.s.l. Half of the 30 GBOs predicted in this massif are thus gathered between 2200 and 2500 m a.s.l., half of the 40 GBOs predicted in the Mont Blanc massif are spread between 1750 and 2750 m a.s.l., and half of the 60 GBOs predicted in the Vanoise massif are found between2500 and 3000. The least and most elevated GBOs are found in the Mont Blanc massif at respectively 1570 m a.s.l. (Mer de Glace) and 4507 m a.s.l. (Bossons glacier), in coherence with glacier distributions.

4.2. Morphological analysis and level of confidence of GBOs

Among the 139 predicted GBOs, 4 cumulate all criteria favouring their existence (see sect. 3.3) and are thus characterized by a very high confidence (100% of criteria are fulfilled). In addition, 28 GBOs have a high confidence and 27 have a medium confidence. Finally, 47 have a low confidence, 31 a very low confidence, and only 2 predicted GBOs are not plausible with an extremely low confidence (fig. 6). No statistical relationship was found between the level of confidence and GBOs morphometrics but none of the larger or deeper GBO has low level of confidence. The deepest GBO (Argentière glacier) and the most voluminous one (Talèfre glacier) are both characterised by high confidence.

Fig. 6 – Level of confidence of the GBOs predicted by GlabTop and GlabTop 2, GBOs visually detected and presence/absence of water body at predicted GBOs.

Fig. 6 – Niveaux de confiance des surcreusements sous glaciaires prédits par GlabTop et GlabTop 2, surcreusements détectés visuellement et présence/absence de surcreusements dans les surcreusements détectés.

A: Mont Blanc massif; B: Ecrins massif; C: Vanoise massif; D: Grandes Rousses massif; E: Ubaye massif. (Coordinate system : Lambert 93 / RGF 93).

A : massif du Mont Blanc ; B : massif des Ecrins ; C : massif de la Vanoise ; D : massif des Grandes Rousses ; E : massif de l'Ubaye. (Système de coordonnées : Lambert 93 / RGF 93).

1. GBO predicted by GlabTop; 2. GBO visually detected; 3. Absence of water body at predicted GBO; 4. Water body at predicted GBO < 0.01 km^2; 5. Water body at predicted GBO in recently deglaciated area; 6. Extremely low confidence; 7. Very low confidence; 8. Low confidence; 9. Medium confidence; 10. High confidence; 11. Very high confidence

1. Surcreusement prédit par GlabTop ; 2. Surcreusement détecté visuellement ; 3. Absence de plan d'eau dans le surcreusement prédit GBO ; 4. Présence de lac ou plan d'eau dans un surcreusement prédit par GlabTop < 0.01 km^2 ; 5. Présence de lac ou plan d'eau dans les secteurs récemment désenglacés ; 6. Niveau de confiance extrêmement bas ; 7. Niveau de confiance très bas ; 8. Niveau de confiance bas ; 9. Niveau de confiance moyen ; 10. Niveau de confiance élevé ; 11. Niveau de confiance très élevé

The Mont Blanc massif gathers 16 of the 32 GBOs with a high and very high confidence. Among the least likely GBOs (low and very low confidence), 73% are located in the Vanoise massif.

In the Mont Blanc massif, the GBOs most likely to exist (very high confidence) are under the Talèfre, Tré la Tête and Bionnassay glaciers, and some GBOs under the Mer de Glace, Miage, Argentière and Tour glaciers have also a high confidence. In the Vanoise massif, the GBOs with the higher level of confidence are located under the Evettes and the Rosolin glaciers (high confidence). The GBOs under the Pramort, the Epéna, and the Gébroulaz glaciers have a medium confidence. In the Ecrins massif, the most plausible GBOs are under the Selette, the Condamines and the Blanc glaciers (high level of confidence).

In the Grandes Rousses massif, the most voluminous GBO under the Saint Sorlin glacier (9 Mm^3) has a low level of confidence. Indications from direct field measurements (geophysics, boreholes) of a possibly overdeepened trough as compiled by Le Meur and Vincent (2003) show that ice thickness reached about 110 m in 1998 at this location and that another GBO (not predicted by GlabTop model runs) may actually exist farther upstream. For the one predicted with GlabTop beneath the present snout of the Saint Sorlin glacier, the absence of a clear bedrock threshold and a marked break in slope explains its rather low level of confidence. The already existing small water bodies in front of the present ice margin had developed during the past decades above a rather weakly marked bedrock threshold and corresponding somewhat smooth break in slope.

4.3. Evaluation of predicted GBOs with water bodies in recently deglaciated ice-marginal areas.

GBOs were predicted using glacier outlines drawn from glacier inventory data acquired between 2004 and 2009 and a corresponding DEM acquired between 2000 and 2010. Since that time, glacier retreat has continued at a fast rate and thereby exposed areas where GBOs had been predicted within but close to the former ice margin. This development makes it possible to investigate sites of predicted GBOs with respect to the questions whether (a) the specific overdeepened topography has been realistically predicted and (b) water bodies indeed developed or not (fig. 7-9). As mentioned before, the second question involves aspects (drainage, permeability, sediment input) beyond general topographic conditions. It must be kept in mind that the applied slope averaging near flat glacier margins is delicate as it involves topographic information from slightly outside the ice margin. Moreover, the assumption of a constant basal shear stress along flow breaks down for retreating and decaying glacier with wedge-like marginal ice geometries causing basal shear stresses to decease towards zero. This effect leads to a systematic overestimation of ice thicknesses towards the ice margin of retreating glaciers and, hence, tends to produce artefacts of adverse slopes. In fact, some of the perennial surface ice bodies from the used glacier inventory are, or have become, extremely small, often disintegrating and collapsing ice remains (*e.g.* Evettes, Méan Martin) at the very limits of the term and concept “glacier” (fig. 9D). A good number of GBOs are still only partially exposed (*e.g.* Grande Motte, Grand Méan, Rhême Golette, Tré la Tête).

With few exceptions (for instance, Blanc Glacier), the predicted GBOs indeed indicate flat to overdeepened parts of formerly ice-covered topography. In cases, the location of the predicted GBO seems to be small or vague (*e.g.* Mulinet), spatially dislocated (*e.g.* Malatres) or to have a rough surface in bedrock (*e.g.* Arpon, Pelve) or coarse debris (*e.g.* Mer de Glace, Tré la Tête) with sometimes small ponds existing in correspondingly small topographic depressions (*e.g.* Arpon, Pelve, Méan Martin, Patinoire, Fond).

Small to medium-size water bodies and lakes have continued to form (*e.g.*, Grand Méan, Montet) or newly started to form (*e.g.*, Rhême Golette) at 17 sites (fig. 6-7). They can be found at or below the snout of the Bionassay, Tré la Tête and Pèlerins glaciers in the Mont Blanc massif, downstream of the Selle glacier and the Fond glacier in the Ecrins massif and 3 others in the Grandes Rousses massif downstream of the Rousses glacier and Sarenne glacier. In the Vanoise massif, 8 lakes are already visible at the front of the Montet, the Grand Méan and the Patinoire glaciers.

Fig. 7 – Visible new water bodies in recently deglaciated areas where GlabTop and GlabTop 2 predicted a GBO. (red areas : slope > 30° ; blue areas : permafrost favourability index > 0.5 (Marcer et al., 2017) for the slopes <35° and permafrost favourability index > 0.5 (Boeckli et al. 2012) for the slopes >35°; black lines : glacier contour 2004-2009 (Gardent et al., 2014) ; white lines : visible lake or water bodies limits; Google Earth images).

Fig. 7 – Lacs ou plans d'eau visibles dans les secteurs récemment désenglacés où GlabTop et GlabTop 2 ont prédit des surcreusements sous glaciaires. *(Zones rouges : pente > 30° ; zones bleues : indice de permafrost > 0.5 (Marcer et al., 2017) pour les pentes <35° indice de permafrost > 0.5 (Boeckli et al. 2012) pour les pentes >35° ; lignes noires : contours des glaciers 2004-2009 (Gardent et al., 2014) ; lignes blanches : limites des lacs et plans d'eau ; images de Google Earth).*

A-C: the Mont Blanc massif; D-K: the Vanoise massif; L-N: the Grandes Rousses massif; O-P: the Ecrins massif.

A-C : le massif du Mont Blanc ; D-K : la Vanoise ; L-N : les Grandes Rousses ; O-P : les Ecrins.

Among these 17 water bodies, 11 have medium, high and very high confidence (≥ 3/5), such as the one the Fond glacier in the Ecrins massif for example (fig. 7P). The others have a low confidence (≤ 2) notably because criteria (ii) and (iii) (break in slope and bedrock threshold) are not fulfilled. In these cases, water bodies are rather small and shallow, if not almost inexistent as this is the case on the Baounet glacier margin (fig. 7I), where only small water bodies are formed in bedrock hollows, but not as voluminous as the GBOs predicted by GlabTop. Furthermore, some lakes are formed in morainic material such as at l'Argentière glacier (Vanoise massif; fig. 7D) where the newly formed water body in a local depression of a gently inclined debris slope is displaced with respect to the predicted GBO. It may not turn into a perennial lake, as it looks very shallow, and may drain with changes in the bottom and front material permeability (cf. Haeberli et al., 2001). This is also the case for the Pèlerins glaciers (Fig. 7A) as already discussed by Magnin et al. (2020).

In the Grandes Rousses massif, 3 lakes have already started to form in 6 of the predicted GBOs (fig. 7. L, M, N), including 2 on the Rousses glacier that is on the west side of the massif where the staircase-like counter slopes form permanent dams that have favoured lake formation (Fig. 7L, M).

It has to be noted that only the predicted GBOs ≥ 0.01 km² are analysed here. However, recently formed pounds or water bodies are also observed in predicted GBOs < 0.01 km² such as at the snouts of the Sources de l'Arc, the Grand Méan and the Ouille Mouta glaciers (fig 6, 8). While those at the Grand Méan glacier are < 0.01 km², the one at Sources de l'Arc glacier, which currently reaches 0,005 km², is partly covered by the glacier and may grow in the future. The one at the snout of the debris-covered Ouille Mouta glacier which is already > 0,02 km² and may also grow more.

Fig. 8 – Visible new water bodies in recently deglaciated areas where GlabTop and GlabTop 2 predicted a GBO ≤ 0.01 km². (Black lines: glacier contour 2004-2009 (Gardent et al., 2014) ; white lines visible lake or water bodies limits; Google Earth images).

***Fig. 8 – Lacs ou plans d'eau visibles dans les secteurs récemment désenglacés où GlabTop et GlabTop 2 ont prédit des surcreusements sous glaciaires* GBO ≤ 0.01 km².** *(Lignes noires : contours des glaciers 2004-2009 (Gardent et al., 2014) ; lignes blanches : limites des lacs et plans d'eau ; images de Google Earth).*

A: Sources de l'Arc glacier; B: Grand Méan glacier; C: Ouille Mouta glacier; D: Grand Méan glacier.

A : Glacier des Sources de l'Arc ; B : Glacier du Grand Méan ; C : Glacier d'Ouille Mouta ; D : Glacier du Grand Méan.

In 15 recently deglaciated GBOs no lake formation is observed (fig. 9A-O). One of them is in the Mont Blanc massif, 11 are found in the Vanoise massif, 2 in the Ecrins massif and 1 exists in the Grandes Rousses massif. In most cases, the absence of water bodies can be explained by a lack of a marked bedrock threshold downstream of the predicted GBO, by a slope that is too steep or by sediment infilling. A large majority (12) of these 15 GBOs have a low and very low level of confidence. Two of them have a medium confidence are at the front of the Pramort (fig. 9K) and Pilatte (fig. 9O) glaciers. For both cases, surface slope is relatively steep and, thus, not favourable for water retention. At the Pilatte glacier, a water stream washes out the supplied sediments and uncovers the bedrock below, showing that there is no overdeepening. At the Pramort glacier, despite the presence of a bedrock threshold downstream, no lake has formed and the glacier forefield is a sediment filled floodplain. At the front of the Grande Motte (fig. 9H) glacier, the GBO has a high confidence as it fills criteria (ii) and (iii), but similarly to the Pilatte glacier, the slope angle >10° did not favour water or sediment retention.

Sometimes, water bodies are observed but could not become perennial lakes such as in front of Vallonnet Inférieur glacier (fig. 9F), where water is accumulating superficially in morainic material at predicted GBO in the same way as the Pramort glacier, the forefield of the debris-covered Vallonet Inferieur glacier is turning into a sediment-filled floodplain.

Fig. 9 – Absence of water bodies in recently deglaciated areas where GlabTop and GlabTop 2 predicted a GBO. (Red areas : slope > 30° ; blue areas : permafrost favourability index > 0.5 (Marcer

et al., 2017) for the slopes <35° and permafrost favourability index > 0.5 (Boeckli et al. 2012) for the slopes >35°; black lines : glacier contour 2004-2009 (Gardent et al., 2014); Google Earth images).

Fig. 9 – Absence de lacs ou de plan d'eau dans les secteurs récemment désenglacés où GlabTop et GlabTop 2 ont prédit des surcreusements sous glaciaires. *(Zones rouges : pente > 30° ; zones bleues : indice de permafrost > 0.5 (Marcer et al., 2017) pour les pentes <35° indice de permafrost > 0.5 (Boeckli et al. 2012) pour les pentes >35° ; lignes noires : contours des glaciers 2004-2009 (Gardent et al., 2014) ; images de Google Earth).*

A: the Mont Blanc massif; B-L: the Vanoise massif; M: the Grandes Rousses massif; N-O the Ecrins massif.

A : le massif du Mont Blanc ; B-L : la Vanoise ; M : les Grandes Rousses ; N-O : les Ecrins.

This preliminary analysis indicates that predicted GBOs are realistic in most cases with higher confidence levels from morphological criteria but that failures also exist, especially in cases with lower confidence levels. Such failures primarily relate to specific geometries (wedge type ice margins) of extremely small, disintegrating and collapsing remains of surface ice and to heavily debris-covered parts of glaciers with their specific imbalance and sediment input. A good number smaller to larger water bodies have indeed formed or continued to form in realistically predicted GBOs. Only smallest water bodies seem to have come into existence where no GBOs were predicted, however, the case of the Source de l'Arc and more specifically the Ouille Mouta glaciers show that large water bodies may form where only insignificant GBOs are predicted. Drainage of exposed GBOs through deep-cut gorges was not evident in any case and seems to be an exception rather than a rule.

4.4. Potential GBOs visually detected

In addition to potential GBOs automatically detected with GlabTop and GlabTop2, 58 GBOs have been visually detected by analysing glacier morphologies with the four criteria used to assess predicted GBOs plausibility. 30 of them have been found in the Vanoise massif, 15 in the Mont Blanc massif, 12 others in the Ecrins massif and 1 in the Grandes Rousses massif (fig. 6). One GBO only visually detected by Magnin et al. (2020) on the Bionnassay glacier (Mont Blanc massif) was eventually also predicted by GlabTop 2 in this study.

According to the morphological analysis, one of these visually detected GBOs in the Ecrins massif has a very high confidence. In addition, 13 of them have high confidence and 33 have a medium confidence, and they are all in the Ecrins, Grandes Rousses, Vanoise or Mont Blanc massifs. Finally, 11 GBOs visually detected have a low confidence.

5. Discussions

5.1. Strengths and limitations in the method

Previous work conducted on the Mont Blanc massif compared 20 profiles of Ice Penetrating Radar (IPR) measurements (Rabatel and al., 2018) and seismic measurements (Vincent & Moreau, 2016) acquired on the Argentière glacier to GlabTop results (Magnin et al., 2020). This comparison confirmed that – despite large uncertainties in absolute values of estimated ice thicknesses – the locations of predicted GBOs as topological units defined by spatial patterns rather than absolute values of ice thickness – were generally robust. The morphological analysis, however, remains necessary to assess the level of plausibility of the numerical predictions. Our study confirms these results (sect. 4.5) but also points out the relevance of combining various methods, including fully or semi-automated detection approaches such as with GlabTop 2 and GlabTop, morphological analysis and visual detection. All these approaches have their respective advantages and drawbacks and can, therefore, provide different but also complementary results. Differences in the GBO morphometrics produced by GlabTop and GlabTop 2 can sometimes be considerable, and can be explained by the fact that GlabTop 2 calculates ice thickness at random points and then interpolates predicted ice thickness at those points and the margins where it is set to 0 (Frey et al., 2014), while such calculation is based on branchlines with GlabTop. Another difference is the DEM resolution (50 m versus 25 m) but a second run of GlabTop with the same 50 m resolution DEM as the one used for GlabTop2 did not explain differences in the results. Additionally, the study from Magnin et al. (2020), which also used GlabTop but with three different DEMs and other sets of branchlines, resulted in variable morphometrics from one DEM to another, but also different in places from those predicted in our study. Furthermore, the latter study shows that depths and volumes of predicted GBOs tend to be general underestimated, with differences up to 50%. This is more than the average 30% uncertainty found in a comparative study by Farinotti and al. (2017) concerning absolute values of estimated ice thicknesses. While GlabTop and GlabTop 2 have both been extensively used, no scientific comparison of the predicted GBOs between the two approaches and their implications for results interpretation have been performed yet. The use of morphological indications related to glacier flow through predicted GBOs is primarily of use for relative comparison. Application of the obtained results for, for instance, modelling of GLOFs from potential future lakes in specific cases requires detailed field investigation to assess GBOs depths, volumes and extent such as IPR measurements or drillings (*e.g.* Le Meur and Vincent 2003, Rabatel et al., 2018).

Furthermore, classification of GBOs according to their levels of confidence is based on more or less subjective determination of criteria fulfilment, such as the slope angle threshold at which a GBO is susceptible to exist or not, or the obviousness of a bedrock threshold. A similar research conducted by another research team could lead to somewhat different appreciation. Implication for the interpretation of results can be minimized by using the confidence level classes instead of the absolute values related to individual criteria or their simple sum. This classification allows to point out GBOs that are obvious and to define the variability in uncertainty which reflects the transitional character in nature of simply flat to markedly overdeepened bed parts.

The constant shear-stress approach used by both GlabTop models becomes especially problematic at firn divides where surface slope and, hence, basal shear stress approaches zero (Paul and Linsbauer, 2012: Guardamino et al. 2019). Estimating glacier-bed topography at firn dived still remains a problem to be solved (ITMIX; Farinotti et al., 2017). In this respect, the 15 GBOs detected in the Vanoise massif on the top of the ice caps should be interpreted with caution and other modelling approaches could be used for such terrain.

Another limitation of our approach is related to debris-covered glaciers because GlabTop assumptions about near-equilibrium conditions may be unrealistic in such cases. Such glaciers are becoming more and more extensive in the French Alps, notably in areas exposed to frequent rockfalls or rock avalanches. 30 GBOs are in this situation in the Mont Blanc massif, 7 in the Vanoise massif, 18 in the Ecrins massifs, 1 in the Grandes Rousses Massif and 2 in the Ubaye massif. In addition, the Ouille Mouta debris-covered glacier recently uncovered a rather large lake where only an insignificant GBO was predicted. Large amounts of debris supplied to glaciers and draining systems could also result in GBOs filling with sediments, hindering the formation of lakes or rapidly terminating their existence. This was the case at the snout of the Mer de Glace where a small lake formed in the 1990s and was soon filled by sediments (Deline et al., 2012; Magnin et al., 2020). In addition, lake formation in highly permeably non-consolidated material may only be temporary. Modelling sediment transport remains a challenge but could help to refine the assessment of future lake formation plausibility. Zemp et al. (2005) have developed a method that converts the sediment balance of a glacier into an erosion-sedimentation index to identify glacier beds consisting of bedrock, sediments, or a mixture of both. This GIS method is automated and could help with estimating sediment input into ice-free GBOs and the potential lifetime of lakes (cf. Linsbauer et al., 2016).

Finally, not all potential GBOs are predicted because of the input data (DEM at 25 and 50 m) which can smooth the topography and the GlabTop model which does not consider glacier width reduction or crevasses (sect. 4.5). Therefore, GlabTop and GlabTop 2 have the main advantage to automatically detect GBOs and to provide basic morphological characteristics at least reliable to compare predicted GBOs to each other, but a visual analysis remains highly relevant for completing potential GBOs detection, even though it does not guarantee an exhaustive estimation of potential GBOs. For example, the study from Le Meur et Vincent (2003) shows a GBO on the upper part of the Saint Sorlin glacier based on interpolation of variable field measurements, upstream of the one which is predicted in this study, but it is not revealed by strikingly obvious morphological criteria.

5.2. GBOs characteristics in the French Alps and implication for hazard assessments

GBOs are on average two times larger in the Mont Blanc massif than in the Ecrins massif and the Vanoise massif (tab. 3) and have the greater ratio of surface area to glacier extent. This may be put in relation with glacier sizes. In the Mont Blanc massif, glaciers > 2.5 km² represent 86% of the massif's glaciated surface area, on the contrary, 75% of the glaciated surface area of the Vanoise and 72% of the Ecrins are covered by glacier < 2.5 km² (Gardent, 2014).

While predicted GBOs remain rather small compared to other high alpine areas in the world such as the Himalaya where they frequently exceed 10^6 m^3 (Linsbauer et al., 2016), their relevance in terms of hazards sources is high because downstream slopes are generally steep adjacent valley floors often are densely occupied in the French Alps. Settlements are quite often right below glacier areas, and mountain flanks are equipped with numerous infrastructures to host a variety of leisure and tourism activities. Mountain communities may thus be affected by possible dangerous high-magnitude and cascading processes associated with recently formed or potential future lakes that can develop in GBOs. Rock/ice avalanches can impact such lakes or morainic dams can suddenly breach (Allen et al., 2016b, 2016a; Ashraf et al., 2012; Clague and Evans, 2000; Emmer, 2017; Hubbard et al., 2005; Schaub et al., 2016; Schneider et al., 2014; Somos-Valenzuela et al., 2016; Worni et al., 2012). A recent example of high-magnitude chain-reaction hazards in the European Alps was associated to the Piz Cengalo rock avalanche in 2017 (3 Mm^3, southern Swiss Alps), which provoked a debris flow that killed 8 people on its way and damaged about 100 infrastructures in the village of Bondo. This hazards chain did not involve any lake but was certainly favoured by the water retained in glacial sediments (Walter et al., 2020), and thus highlights how damaging such hazards could be, notably if the mass movement hits an open water body. Possible hazard issues also have to be analysed in the light of recent studies demonstrating an accentuated glacial retreat in response to summer heat waves (Rabatel et al., 2013), which also provoke permafrost degradation and enhanced rockfall activity (Ravanel and Deline, 2011; Ravanel et al., 2010; 2017; Walter et al., 2020). Therefore, glacial lakes located at the foot of high mountain rock walls subject to debuttressing and/or permafrost degradation can become evident “hot spots”.

In this respect, the Mont Blanc massif appears as the most exposed one with 50% of the most plausible GBOs, the most voluminous ones (under the Talèfre, Tré la Tête glacier and Argentière glaciers). Given that the Chamonix valley is densely populated with 8 759 inhabitants (INSEE, 2016) with an high tourism frequentation (12 304 700 overnight stays in 2016 in the *Pays du Mont Blanc*; Savoie Mont Blanc Tourisme, 2017), that the mountain flanks are roamed by mountaineers, hikers and contemplative tourists (1,619,426 tickets for the Montenvers train and the Aiguille du Midi cable car; Savoie Mont Blanc Tourisme, 2017), risks associated to sudden lake draining are exacerbated. Magnin et al. (2020) have already pointed out potential future lakes located right below high-elevated permafrost rockwalls in the Mont Blanc massif (the Pélerins or Miage glacier for example) but also suggested possible lakes that could become future opportunities for water supply (*e.g.* Tour glacier). Hazard potentials would have to be carefully assessed (GAPHAZ, 2017) in such cases. In addition, these results also raise questions in terms of attractiveness for tourism related to the perceptions of glacial and periglacial landscapes (Salim et al., 2019).

In the Vanoise massif, despite many predicted GBOs have a rather low level of confidence, they might be considered as there are also many touristic infrastructures, like mountain huts or ski resorts. When considering levels of confidence, potential volumes, the presence of steep slopes and permafrost upstream, and possible vulnerabilities, the Evettes glacier, the Rosolin glacier and the Epéna glacier (fig. 10) could become hot spots as they are located right below the 700-m-high north face of the Grande Casse (3855 m a.s.l.), which is still affected by permafrost according to the map from Boeckli et al. (2012) and feed the Doron de Champagny, that reach the touristic village of Champagny-en-Vanoise about 10 km below. Historically, Champagny-en-Vanoise has already known major GLOF events, notably in 1818 when the Glière lake became obstructed by the l’Epéna glacier tongue and suddenly discharged 3.7 Mm^3 in the Doron de Champagny and caused severe damages (Mougin, 2001). More recently, the lake that formed at the snout of the Patinoire glacier (fig. 7K) already outburst in 1964 because of the impact of an ice fall from the Vallonet glacier, causing an impact wave which triggered breaching of its morainic dam. The village of Pralognan-la-Vanoise was partly flooded and bridges and cars were swept up. At present, the Vallonet glacier has vanished but this lake remains a possible hot spot as it is surrounded by steep slopes.

Fig. 10 – Example of possible hot spots in the Vanoise massif: The Epena and the Rosolin Glacier. (Red areas: slope > 30°; blue areas: permafrost favourability index > 0.5 (Marcer et al., 2017) for the slopes <35° and permafrost favourability index > 0.5 (Boeckli et al. 2012) for the slopes >35°; Google Earth image).

Fig. 10 – Exemple de hot spot possible dans le massif de la Vanoise : le glacier de l'Epena et le glacier de Rosolin. *(Zones rouges : pente > 30° ; zones bleues : indice de permafrost > 0.5 (Marcer et al., 2017) pour les pentes <35° indice de permafrost > 0.5 (Boeckli et al. 2012) pour les pentes >35° ; image de Google Earth).*

1. GBO predicted with GlabTop; 2. GBO visually detected; 3. High confidence; 4. Medium confidence; 5. Absence of water body.

1. Surcreusement prédit par GlabTop ; 2. Surcreusement détecté visuellement ; 3. Confiance élevée ; 4. Confiance moyenne ; 5. Absence de lac ou de plan d'eau.

In the Ecrins massif, such hot spots would be at the Fond glacier, the Sellettes glacier, the Condamines glacier, the Vallon des Etages glacier and the Blanc glacier. There, the predicted GBOs are located directly upstream from mountain huts like the Lavey refuge (under the Fond and Sellettes glaciers, fig.11) and the Gioberney Chalet-Hotel (downstream from the Condamines glacier) and right below steep slopes.

It is nevertheless necessary to keep in mind that those potential lakes will form at different times. The 19 water bodies or lakes identified in recently deglaciated areas (sect.4.3), may be considered as "in formation" (*e.g.* Grand Méan glacier) or fully formed (*e.g.* Rousses glaciers) and other lakes predicted with GlabTop could form imminently (*e.g.* Talèfre glacier; Sellettes glacier) considering their low altitude and the current high glacier retreat rate. However, the lakes predicted in GBOs at high altitudes such as the ones possible underneath the ice cap (*e.g.* under the Pelve, Arpon and Arcelin glaciers) or upstream of glaciers (*e.g.* Géant glacier; top of the Blanc glacier) could form later in the century.

Fig. 11 – Example of possible hot spots in the Ecrins massif: The Fond and the Sellettes Glacier. (Red areas: slope > 30°; blue areas: permafrost favourability index > 0.5 (Marcer et al., 2017) for the slopes <35° and permafrost favourability index > 0.5 (Boeckli et al. 2012) for the slopes >35 Google Earth image).

Fig. 11 – Exemple de hot spot possible dans le massif des Ecrins : le glacier du Fond et le glacier des Sellettes. *(Zones rouges : pente > 30° ; zones bleues : indice de permafrost > 0.5 (Marcer et al., 2017) pour les pentes <35° indice de permafrost > 0.5 (Boeckli et al. 2012) pour les pentes >35° ; image de Google Earth).*

1. GBO predicted with GlabTop; 2. Observed water body in recently deglaciated forefields; 3. High confidence.

1. Surcreusement prédit par GlabTop ; 2. Lacs déjà formés dans les sur les fronts récemment désenglacés ; 3. Confiance élevée.

6. Conclusions et perspectives

This study aimed to identify GBOs as possible locations for future lakes, by modelling glacier bed topography with GlabTop and GlabTop 2 in the French Alps. The predicted GBOs were classified according to their level of confidence which was established based on a morphological analysis accounting for slope angle at and downstream of the predicted GBOs, the presence/absence of bedrock threshold and the presence/absence of a crevasse field downstream. The main outcomes are the following:

- The predicted GBOs quite reliably indicate flat to markedly overdeepened parts of glacier beds, the latter especially – but not exclusively – where morphological indications are strong. Artefacts and failures must be expected at wedge-type ice margins of rapidly retreating to even decaying small glaciers and at heavily debris covered glacier tongues where sediment input is high. However, no significant water body was found were no GBO was predicted.
- 139 GBOs are predicted (after sorting out GlabTop and GlabTop 2 output to avoid duplicated GBOs) and represent a total surface area of 9.48 km² (3.5% of the glacier surface area), about which 50% are in the Mont Blanc massif (40 GBOs), 30% in the Vanoise massif (60 GBOs) and 16% in the Ecrins massif (30 GBOs). They also represent a total volume of 217.4 Mm^3, 67% of which is in the Mont Blanc massif, 19% in the Vanoise massif and 9% in the Ecrins massif.
- Their altitudinal distribution is directly related to the one of the related glaciers with the least elevated GBOs predicted in the Mont Blanc massif were glaciers reach the lowest

elevation. However, the Ecrins massif gathers half of its predicted GBOs between 2200 and 2500 m a.s.l., while this lower half is more stretched for the other massifs (2500 – 3000 m a.s.l. for the Vanoise and 1750-2750 for the Mont Blanc massif). Only one single GBO is predicted > 3500 m a.s.l.

- Among the 139 predicted GBOs, 59 have a medium, high and very high confidence (≥ 3/5), which means that they are they are likely to exist, and 50 % of them are in the Mont Blanc massif. However, 73 % of GBOs with a low and very low confidence (≤ 1/5) are in the Vanoise massif which hosts many ice-cap like glaciers with firn divides which are not easily treated with the here-applied approaches. Larger and deeper GBOs all have a medium to high level of confidence.
- The larger, deeper and most voluminous GBOs are predicted in the Mont Blanc massif, the deepest one being at the Argentière glacier (146 m) and the most voluminous one at the Talèfre glacier (24.8 Mm^3), both characterised by high levels of confidence.
- 17 predicted GBOs (> 0.01 km^2) at recently deglaciated forefields have already yielded a water body. The confidence levels of the predictions were generally high for these cases. In 15 cases of GBO predictions at generally low confidence levels, dry conditions are combined with the absence of marked bedrock threshold, relatively steep slopes > 10-15°, or dynamic sediment infilling. Additionally, 2 lakes already > 0,01 km^2 or that could reach that size in the future have started to form where GBOs < 0,01 km were predicted.
- In addition to the GlabTop results, 58 GBOs have been visually detected by analysing glacier morphologies, among which 30 are in the Vanoise massif, 15 in the Mont Blanc massif, 12 in the Ecrins massif and 1 in the Grandes Rousses massif. 4 of them are > 3500 m a.s.l.

Our study provides key-information about rapidly emerging high-mountain landscapes as a consequence of glacier retreat to even vanishing. It represents an essential first step for potential future research, which will constitute a basis of reflection for decision-makers in long-term planning. Although the predicted depths and volumes of GBOs remain uncertain, their location and level of confidence are relevant to anticipate potential future lake formation and to highlight possible hot spots in terms of GLOF hazards, but also to recognize opportunities related to water resources, hydropower production and tourism in the French Alps. The resulting inventory of potential future lakes especially indicates where more detailed investigation should be conducted in areas of interest. This could involve modelling of glacier retreat to assess the time range under which potential lakes could form, geophysical soundings to assess GBOs morphometrics, or numerical model calculations of potentially involved process chains following rock/ice avalanches and related displacement/flood waves or debris flows to assess possible impacts, hazards and risks to humans and their infrastructure.

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