



**HAL**  
open science

# Modelling glacier-bed overdeepenings as sites for possible future lakes in deglaciating landscapes of the French Alps

Maëva Cathala, Florence Magnin, Andreas Linsbauer, Wilfried Haerberli

► **To cite this version:**

Maëva Cathala, Florence Magnin, Andreas Linsbauer, Wilfried Haerberli. Modelling glacier-bed overdeepenings as sites for possible future lakes in deglaciating landscapes of the French Alps. *Géomorphologie: relief, processus, environnement*, 2021, 27 (1), pp.19-36. 10.4000/geomorphologie.15255 . hal-03024111

**HAL Id: hal-03024111**

**<https://hal.science/hal-03024111>**

Submitted on 25 Nov 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Copyright

1 Modelling glacier-bed overdeepenings as sites for possible future lakes in deglaciating  
2 landscapes of the French Alps

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

5 **Authors:** M. Cathala\*<sup>1</sup>, F. Magnin<sup>1</sup>, A. Linsbauer<sup>2,3</sup>, W. Haeberli<sup>2</sup>

6 <sup>1</sup> Edytem laboratory – UMR 5204 CNRS – Savoie Mont Blanc University – 73376 Le Bourget du Lac  
7 – France

8 <sup>2</sup> Geography Department – University of Zurich – 8057 Zurich – Switzerland

9 <sup>3</sup> Department of Geosciences – University of Fribourg – 1700 Fribourg – Switzerland

10  
11 maeva.cathala@yahoo.fr (Maëva Cathala)

12 florence.magnin@univ-smb.fr (Florence Magnin)

13 andreas.linsbauer@geo.uzh.ch (Andreas Linsbauer)

14 wilfried.haeberli@geo.uzh.ch (Wilfried Haeberli)

15  
16 \*Maëva Cathala : Tel : +33 (0) **x xx xx xx xx**

17  
18 **Abstract**

19 Glacier retreat results in major landscape changes including the formation of new lakes in  
20 Glacier-Bed Overdeepenings (GBOs) that can provoke catastrophic Glacial Lake Outburst  
21 Flood (GLOF) hazards, but could also provide economic opportunities. This study aimed to  
22 identify and characterize the location of potential GBOs in the French Alps as possible sites for  
23 future lakes. We first ran GlabTop (Glacier-bed Topography) and GlabTop 2 models, two GIS  
24 schemes calculating glacier ice thickness and mapping potential GBOs. Their level of  
25 confidence is estimated using morphological analysis based on slope angle, crevasse fields and  
26 lateral narrowing at bedrock thresholds. 139 GBOs (> 0.01 km<sup>2</sup>) were predicted among which  
27 59 have medium to very high confidence. 19 lakes are already forming at the snout of retreating  
28 glaciers, including 2 lakes at predicted GBOs < 0,01km<sup>2</sup>. The Vanoise massif hosts 43% of the  
29 predicted GBOs but the Mont Blanc massif gathers larger, deeper and more voluminous ones.  
30 Most of the predicted GBOs are below 3500 m a.s.l. and is related to that of glaciers. In the  
31 Vanoise massif, many predicted GBOs have rather low level of confidence because of the extent  
32 of ice-cap like glaciers for which the shear stress approach used by GlabTop becomes

33 questionable. Furthermore, 58 potential GBOs were detected by visual analysis of glacier  
34 morphologies. The study highlights the relevance of combining various methods to determine  
35 GBOs and is a first step towards the anticipation of future risks and opportunities related to the  
36 formation of new lakes in the French Alps.

37

### 38 **Résumé**

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

58

### 59 **Keywords**

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

62

### 63 **Mots clés**

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

## 66 1. Introduction

67 Global warming is particularly pronounced in high mountain environments and has accelerated  
68 in the past decades (IPCC, 2019). In the French Alps, air temperature has increased by +1.5 °C  
69 to +2.1 °C since 1950 (Einhorn et al., 2015). This has strong impacts on the Alpine cryosphere,  
70 such as rising of the rain-snow limit by about 400 m since the 1980s (Böhm et al., 2010),  
71 permafrost degradation (Magnin et al., 2017; PERMOS, 2019) and glacier retreat (Zemp et al.,  
72 2015). In the European Alps, glacier surface area has decreased by 50% and lost 200 km<sup>3</sup>  
73 between the end of the Little Ice Age (LIA, 1850) and 2000 (Zemp et al., 2006). This trend has  
74 clearly accelerated in the recent decades (Huss, 2012; Zekollari et al., 2019).

75 The ongoing deglaciation results in an extension of periglacial environments and sometimes of  
76 new lakes forming in glacier bed overdeepenings (GBO). These lakes are by essence located in  
77 unstable and transient environments. They could be a source of natural hazards related to  
78 Glacial Lake Outburst Floods (GLOF) that could be provoked by sudden dam break or by  
79 displacement waves triggered by mass movements (Allen et al., 2016b; Ashraf et al., 2012;  
80 Clague and Evans, 2000; Emmer, 2017; Hubbard et al., 2005). Glacial lakes are sometimes  
81 located near potentially unstable slopes subject to debulking and/or permafrost degradation  
82 and can amplify gravitational hazards such as rock avalanches (Haeberli et al., 2017) provoking  
83 chains of processes that can travel over long distances and reach valley floors (Byers et al.,  
84 2018 ; Walter et al., 2020). When such far-reaching cascading processes happen in densely  
85 populated valleys, the socio-economic impacts can be dramatic (Carey, 2005, 2012).

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

89 Nevertheless, GBOs not always turn into perennial lakes as they are sometimes filled with  
90 sediments, or they can drain when lakes form in permeable morainic material (Haeberli et al.,  
91 2001). In the French Alps, this was for example the case at the front of the emblematic Mer de  
92 Glace (Mont Blanc massif) where a lake was present in the 1990s but was progressively filled  
93 with sediments (Deline et al. 2012; Magnin et al., 2020) or at the snout of Pèlerin glacier where  
94 a lake formed in 2015 but drained in 2016 (Magnin et al., 2020).

95 Recently developed models, based on variable physical simplifications and input data are able  
96 to calculate spatially distributed ice thicknesses (Farinotti et al., 2009) and the resulting sub-  
97 glacial topography, revealing the location of potential GBOs in which lakes could form  
98 (Linsbauer et al., 2009, 2012; Paul and Linsbauer, 2012). Such studies have already been

99 conducted in various mountain ranges such as, for instance, the Himalayas (Linsbauer et al.,  
100 2016), in Peruvian Andes (Colonia et al. 2015; Drenkhan et al., 2018), Central Asia (Kapitsa et  
101 al., 2017) and in Switzerland (Linsbauer et al., 2012). They are a necessary first step towards  
102 assessing GLOFs hazards and their impacts (GAPHAZ, 2017) and integrative modelling of  
103 future landscapes in glacial and periglacial areas (Haeberli, 2017). In the French Alps, potential  
104 future lakes have so far been investigated in the Mont Blanc massif (Magnin et al., 2020).

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

116

## 117 **2. The French Alps, a deglaciating mountain range**

118 The French Alps are the western edge of the European Alpine arc and extend from the Mont  
119 Blanc massif in the north to the Mercantour adjoining the Mediterranean Sea in the south. With  
120 the Pyrenees, it is one of the two, but also the most glacierized mountain range in the mainland  
121 of France. According to the inventory by Gardent et al., 581 glaciers were counted in  
122 2006/2009, covering 275,4 km<sup>2</sup>. The smallest is a glacieret in the Ecrins massif (Bans glacier –  
123 0.0015 km<sup>2</sup>) and the largest is the Mer de Glace in the Mont Blanc massif (30.5 km<sup>2</sup>). They are  
124 mostly located in the three highest-elevated massifs: Mont Blanc (83 glaciers), Vanoise (174)  
125 and Ecrins massifs (282). Some small glaciers also exist in the Belledonnes, Grandes Rousses  
126 and Ubaye massifs (fig. 1), while only glacierets persist in the Mercantour.

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

132 According to Gardent et al. (2014), glaciers have lost about half of their surface area between  
133 the end of the LIA and the 2006/2009 period in the Ecrins, Vanoise and Mont Blanc massifs.  
134 These authors also explain that glacier recession was 2.5 times faster between the 1967-1971  
135 and 2006-2009 periods than between the end of the LIA and 1967-1971, with a decrease in  
136 glacier surface area of about 25% over the more recent period. Due to glacier retreat, Gardent  
137 (2014) inventoried 443 new ponds and lakes in proglacial areas since the LIA, of which 227 are  
138 over 500 m<sup>2</sup>. Of these larger water bodies, 14 are located behind potentially unstable dams  
139 consisting of non-consolidated morainic material).

140

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

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

145

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

156

### 157 **3. Methods and data**

158 The approach for determining GBOs as possible future lake locations in the French Alps is  
159 conducted by first running GlabTop and GlabTop 2 models, which use the same basic  
160 assumptions but differ by their level of automation. Then, after comparing and compiling results  
161 of both models, a morphological analysis is conducted on each predicted GBO to evaluate the  
162 level of confidence attributed to the prediction. We also evaluate the predictions by comparing  
163 recently formed water bodies and locations of simulated GBOs. Finally, we complete our

164 investigation with a visual analysis of potential GBOs that would possibly have been  
165 overlooked by GlabTop approaches.

166

### 167 3.1. Modelling GBOs with GlabTop and GlabTop 2

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

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

182 We run GlabTop and GlabTOP 2 with the 25 m resolution DEM of the French Institute for  
183 Geography (IGN), the data basis of which was acquired between 2000 and 2010. As GlabTop2  
184 performs reliable on a DEM resolution between 50 to 100 m, we resampled the input DEM to  
185 50 m resolution. Glacier outlines were the ones from Gardent et al. (2014) drawn from  
186 orthorectified photographs taken between 2004 and 2009. Those are not the most updated  
187 contour lines, but they have the advantage to cover recently deglaciating forefield areas where  
188 lakes may, or may not, have formed and could be compared with predicted GBOs (sect. 3.2).  
189 Furthermore, the outlines (2004-2009) fit with the DEM (2000-2010), which is also important  
190 point for GlabTop modelling. To run GlabTop, branch lines were manually digitized on each  
191 glacier following advices from Paul and Linsbauer (2012), that is from bottom to top and  
192 perpendicularly to the contour lines of surface elevation. Each branch line ends about 100 m  
193 from the glacier outline and branch lines have a width interval of 200 m to 400 m.

194 To analyse the model results, the outputs of GlabTop and GlabTop 2 are combined. Where  
195 GBOs are predicted with both models, those from GlabTop 2 are removed. The morphometric

196 characterization of predicted GBOs is thus mostly based on those predicted with GlabTop, but  
197 in most cases, the location is confirmed with GlabTop2.

198

### 199 3.2. Evaluation of GlabTop results

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

207

### 208 3.3. Determining the level of confidence for the predicted GBOs

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

219

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

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

224

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

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



229 -  $(\sum 4 \text{ criteria}) / 20 \times 100$

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

- 232 -  $< 10\%$  = extremely low confidence (0/5)
- 233 -  $\geq 10\% < 30\%$  = very low confidence (1/5)
- 234 -  $\geq 30\% < 50\%$  = low confidence (2/5)
- 235 -  $\geq 50\% < 70\%$  = medium confidence (3/5)
- 236 -  $\geq 70\% < 90\%$  = high confidence (4/5)
- 237 -  $\geq 90\%$  = very high confidence (5/5)

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

242

243 3.4. Visual identification of other potentials GBOs.

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

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

259

260 **4. Results**

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

266

267 4.1.Characteristics of the predicted GBOs

268 4.1.1. *General features and data sorting*

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

270

271 **Fig. 1 – GBOs predicted with GlabTop (yellow lines) and GlabTop 2 (orange lines).**

272 ***Fig. 2 – Surcreusements sous glaciaires prédits par GlabTop (lignes jaune) et GlabTop 2 (lignes***  
273 ***orange).***

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

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

278 (MdG: Mer de Glace; Pel.: Pèlerins glacier; L.: Leschaux glacier; Bos.: Bossons glacier; Tac.: Taconnaz  
279 glacier; Bio.: Bionnassay glacier; T.T.: Tré la Tête Glacier; Inv.: Invernet glacier; l'Ar.: l'Argentière  
280 glacier; Gur.: Gurraz glacier; Fd.: Fond glacier; Sas.: Sassièrè glacier; R.G.: Rhêmes Golette glacier;  
281 Pra.: Pramort glacier; GM.: Grande Motte glacier; Ros.: Rosolin glacier; Ep.: Epéna glacier; Arc.:  
282 Arcelin glacier; Mar.: Grand Marchet glacier; Geb.: Gebroulaz glacier; Chav.: Chavière glacier; Pis.:  
283 Pisailles glacier; Mo.: Montet glacier; Gef.: Géfret glacier; M.M.: Méan Martin glacier; VInt.: Vallonnet  
284 glacier; Va.I.: Vallonnet Inférieur glacier; Va.S.: Vallonnet Supérieur glacier; SdA.: Sources de l'Arc  
285 glacier; Mul.: Mulinet glacier; G.M.: Grand Méan glacier; Son.: Sonailles; Evet.: Evettes glacier; G.F.:  
286 Grand Fond glacier; Mic.: Roche Michel glacier; Bao.: Baounet glacier; Mel.: Rochemelon glacier;  
287 Som.: Sommelier glacier; Mt.L.: Mont de Lans glacier; Gir.: Girose glacier; Rat.: Rateau glacier; PdA.:  
288 Plate des Agneaux glacier; B.P.: Bonne Pierre glacier; VdE: Vallon des Etages glacier; Char.: Chardon  
289 glacier; S.W.: Sellettes glacier West; S.E.: Sellettes glacier East; Pil.: Pilatte glacier; Cond.: Condamines  
290 glacier; Bar.: Barbarate glacier).

291

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

294

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

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

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

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

304

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

316

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

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

321

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

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

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

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

342

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

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

347

348 *4.1.2. Surface areas of predicted GBOs*

349 The predicted GBOs represent a total surface area of  $9.48 \text{ km}^2$ , about 3.5% of the glacier surface  
350 area. Half of it is in the Mont Blanc massif ( $4.81 \text{ km}^2$ , 4.7% of the glacier surface area in the  
351 Mont Blanc massif), about 29% in the Vanoise massif ( $2.74 \text{ km}^2$ , 3% of the glacier surface area  
352 in Vanoise massif) and 16% in the Ecrins massif ( $1.56 \text{ km}^2$ , 2.3% of the glacier surface area in  
353 Ecrins massif; tab. 3).

354

355 **Table 3 – Number and morphological characteristics of the predicted GBOs in each massifs of the**  
356 **French Alps when combining GlabTop and GlabTop 2 results and suppressing the duplicated**  
357 **GBOs.**

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

361

362 The largest calculated GBOs, that are in the Mont Blanc massif (fig. 5), would be at the  
363 confluence of the Leschaux and Tacul glacier (top of the Mer de Glace), and at the Tré la Tête  
364 and Talèfre glaciers, with an area of 0.6 km<sup>2</sup>, 0.52 km<sup>2</sup> and 0.47 km<sup>2</sup> respectively. In the Vanoise  
365 massif, the two GBOs that would have the largest surface area are under the Arcelin glacier  
366 (0.25 km<sup>2</sup>) and the Evettes glacier (0.21 km<sup>2</sup>). In the Ecrins massif, the two largest GBOs are  
367 both found under the Blanc glacier with a surface area of 0.23 km<sup>2</sup> and 0.22 km<sup>2</sup> respectively.  
368 Finally, another relatively large GBOs was predicted under the Saint Sorlin glacier with a  
369 surface area of 0.25 km<sup>2</sup> in the Grandes Rousses massif.

370

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

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

375

#### 376 4.1.3. Depth of predicted GBOs

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

380 In the Vanoise massif, the deepest GBOs are under Evettes glacier (75 m) and Rosolin glacier  
381 (65.5 m). In the Ecrins massif, the deepest GBOs are under the Noir glacier (47 m) and the  
382 Blanc glacier (45 m). Lastly, the GBO under the Saint Sorlin Glacier in the Grandes Rousses  
383 massif is deeper than the ones in the Ecrins an Vanoise with 81 m.

384

#### 385 4.1.4. Volume of predicted GBOs

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

395

396 *4.1.5. Altitude of the predicted GBOs*

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

407

408 *4.2. Morphological analysis and level of confidence of GBOs*

409 Among the 139 predicted GBOs, 4 cumulate all criteria favouring their existence (see sect. 3.3)  
410 and are thus characterized by a very high confidence (100% of criteria are fulfilled). In addition,  
411 28 GBOs have a high confidence and 27 have a medium confidence. Finally, 47 have a low  
412 confidence, 31 a very low confidence, and only 2 predicted GBOs are not plausible with an  
413 extremely low confidence (fig. 6). No statistical relationship was found between the level of  
414 confidence and GBOs morphometrics but none of the larger or deeper GBO has low level of  
415 confidence. The deepest GBO (Argentière glacier) and the most voluminous one (Talèfre  
416 glacier) are both characterised by high confidence.

417

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

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

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

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

427 1. GBO predicted by GlabTop; 2. GBO visually detected; 3. Absence of water body at predicted GBO;  
428 4. Water body at predicted GBO < 0.01 km<sup>2</sup>; 5. Water body at predicted GBO in recently deglaciating  
429 area; 6. Extremely low confidence; 7. Very low confidence; 8. Low confidence; 9. Medium confidence;  
430 10. High confidence; 11. Very high confidence

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

436

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

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

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

457

458 4.3. Evaluation of predicted GBOs with water bodies in recently deglaciating ice-marginal  
459 areas.

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

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

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

491



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

497 *Fig. 7 – Lacs ou plans d'eau visibles dans les secteurs récemment désenglacés où GlabTop et GlabTop*  
498 *2 ont prédit des surcreusements sous glaciaires.* (Zones rouges : pente  $> 30^\circ$  ; zones bleues : indice de  
499 permafrost  $> 0.5$  (Marcer et al., 2017) pour les pentes  $< 35^\circ$  indice de permafrost  $> 0.5$  (Boeckli et al.  
500 2012) pour les pentes  $> 35^\circ$  ; lignes noires : contours des glaciers 2004-2009 (Gardent et al., 2014) ;  
501 lignes blanches : limites des lacs et plans d'eau ; images de Google Earth).

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

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

505

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

518 In the Grandes Rousses massif, 3 lakes have already started to form in 6 of the predicted GBOs  
519 (fig. 7. L, M, N), including 2 on the Rousses glacier that is on the west side of the massif where  
520 the staircase-like counter slopes form permanent dams that have favoured lake formation (Fig.  
521 7L, M).

522 It has to be noted that only the predicted GBOs  $\geq 0.01 \text{ km}^2$  are analysed here. However, recently  
523 formed ponds or water bodies are also observed in predicted GBOs  $< 0.01 \text{ km}^2$  such as at the  
524 snouts of the Sources de l'Arc, the Grand Méan and the Ouille Mouta glaciers (fig 6, 8). While  
525 those at the Grand Méan glacier are  $< 0.01 \text{ km}^2$ , the one at Sources de l'Arc glacier, which  
526 currently reaches  $0,005 \text{ km}^2$ , is partly covered by the glacier and may grow in the future. The

527 one at the snout of the debris-covered Ouille Mouta glacier which is already  $> 0,02 \text{ km}^2$  and  
528 may also grow more.

529

530 **Fig. 8 – Visible new water bodies in recently deglaciated areas where GlabTop and GlabTop 2**  
531 **predicted a GBO  $\leq 0.01 \text{ km}^2$ .** (Black lines: glacier contour 2004-2009 (Gardent et al., 2014) ; white  
532 lines visible lake or water bodies limits; Google Earth images).

533 *Fig. 8 – Lacs ou plans d'eau visibles dans les secteurs récemment désenglacés où GlabTop et GlabTop*  
534 *2 ont prédit des surcreusements sous glaciaires GBO  $\leq 0.01 \text{ km}^2$ . (Lignes noires : contours des*  
535 *glaciers 2004-2009 (Gardent et al., 2014) ; lignes blanches : limites des lacs et plans d'eau ; images de*  
536 *Google Earth).*

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

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

540

541 In 15 recently deglaciated GBOs no lake formation is observed (fig. 9A-O). One of them is in  
542 the Mont Blanc massif, 11 are found in the Vanoise massif, 2 in the Ecrins massif and 1 exists  
543 in the Grandes Rousses massif. In most cases, the absence of water bodies can be explained by  
544 a lack of a marked bedrock threshold downstream of the predicted GBO, by a slope that is too  
545 steep or by sediment infilling. A large majority (12) of these 15 GBOs have a low and very low  
546 level of confidence. Two of them have a medium confidence are at the front of the Pramort (fig.  
547 9K) and Pilatte (fig. 9O) glaciers. For both cases, surface slope is relatively steep and, thus, not  
548 favourable for water retention. At the Pilatte glacier, a water stream washes out the supplied  
549 sediments and uncovers the bedrock below, showing that there is no overdeepening. At the  
550 Pramort glacier, despite the presence of a bedrock threshold downstream, no lake has formed  
551 and the glacier forefield is a sediment filled floodplain. At the front of the Grande Motte (fig.  
552 9H) glacier, the GBO has a high confidence as it fills criteria (ii) and (iii), but similarly to the  
553 Pilatte glacier, the slope angle  $>10^\circ$  did not favour water or sediment retention.

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

558

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

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

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

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

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

571

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

583

#### 584 4.4. Potential GBOs visually detected

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

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

595

## 596 **5. Discussions**

### 597 5.1. Strengths and limitations in the method

598 Previous work conducted on the Mont Blanc massif compared 20 profiles of Ice Penetrating  
599 Radar (IPR) measurements (Rabatel and al., 2018) and seismic measurements (Vincent &  
600 Moreau, 2016) acquired on the Argentière glacier to GlabTop results (Magnin et al., 2020).  
601 This comparison confirmed that – despite large uncertainties in absolute values of estimated ice  
602 thicknesses – the locations of predicted GBOs as topological units defined by spatial patterns  
603 rather than absolute values of ice thickness – were generally robust. The morphological  
604 analysis, however, remains necessary to assess the level of plausibility of the numerical  
605 predictions. Our study confirms these results (sect. 4.5) but also points out the relevance of  
606 combining various methods, including fully or semi-automated detection approaches such as  
607 with GlabTop 2 and GlabTop, morphological analysis and visual detection. All these  
608 approaches have their respective advantages and drawbacks and can, therefore, provide  
609 different but also complementary results. Differences in the GBO morphometrics produced by  
610 GlabTop and GlabTop 2 can sometimes be considerable, and can be explained by the fact that  
611 GlabTop 2 calculates ice thickness at random points and then interpolates predicted ice  
612 thickness at those points and the margins where it is set to 0 (Frey et al., 2014), while such  
613 calculation is based on branchlines with GlabTop. Another difference is the DEM resolution  
614 (50 m versus 25 m) but a second run of GlabTop with the same 50 m resolution DEM as the  
615 one used for GlabTop2 did not explain differences in the results. Additionally, the study from  
616 Magnin et al. (2020), which also used GlabTop but with three different DEMs and other sets of  
617 branchlines, resulted in variable morphometrics from one DEM to another, but also different in  
618 places from those predicted in our study. Furthermore, the latter study shows that depths and  
619 volumes of predicted GBOs tend to be general underestimated, with differences up to 50%.  
620 This is more than the average 30% uncertainty found in a comparative study by Farinotti and  
621 al. (2017) concerning absolute values of estimated ice thicknesses. While GlabTop and  
622 GlabTop 2 have both been extensively used, no scientific comparison of the predicted GBOs  
623 between the two approaches and their implications for results interpretation have been  
624 performed yet. The use of morphological indications related to glacier flow through predicted  
625 GBOs is primarily of use for relative comparison. Application of the obtained results for, for  
626 instance, modelling of GLOFs from potential future lakes in specific cases requires detailed

627 field investigation to assess GBOs depths, volumes and extent such as IPR measurements or  
628 drillings (*e.g.* Le Meur and Vincent 2003, Rabatel et al., 2018).

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

638 The constant shear-stress approach used by both GlabTop models becomes especially  
639 problematic at firm divides where surface slope and, hence, basal shear stress approaches zero  
640 (Paul and Linsbauer, 2012; Guardamino et al. 2019). Estimating glacier-bed topography at firm  
641 dived still remains a problem to be solved (ITMIX; Farinotti et al., 2017). In this respect, the  
642 15 GBOs detected in the Vanoise massif on the top of the ice caps should be interpreted with  
643 caution and other modelling approaches could be used for such terrain.

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

659 mixture of both. This GIS method is automated and could help with estimating sediment input  
660 into ice-free GBOs and the potential lifetime of lakes (cf. Linsbauer et al., 2016).

661 Finally, not all potential GBOs are predicted because of the input data (DEM at 25 and 50 m)  
662 which can smooth the topography and the GlabTop model which does not consider glacier  
663 width reduction or crevasses (sect. 4.5). Therefore, GlabTop and GlabTop 2 have the main  
664 advantage to automatically detect GBOs and to provide basic morphological characteristics at  
665 least reliable to compare predicted GBOs to each other, but a visual analysis remains highly  
666 relevant for completing potential GBOs detection, even though it does not guarantee an  
667 exhaustive estimation of potential GBOs. For example, the study from Le Meur et Vincent  
668 (2003) shows a GBO on the upper part of the Saint Sorlin glacier based on interpolation of  
669 variable field measurements, upstream of the one which is predicted in this study, but it is not  
670 revealed by strikingly obvious morphological criteria.

671

## 672 5.2. GBOs characteristics in the French Alps and implication for hazard assessments

673 GBOs are on average two times larger in the Mont Blanc massif than in the Ecrins massif and  
674 the Vanoise massif (tab. 3) and have the greater ratio of surface area to glacier extent. This may  
675 be put in relation with glacier sizes. In the Mont Blanc massif, glaciers  $> 2.5 \text{ km}^2$  represent 86%  
676 of the massif's glaciated surface area, on the contrary, 75% of the glaciated surface area of the  
677 Vanoise and 72% of the Ecrins are covered by glacier  $< 2.5 \text{ km}^2$  (Gardent, 2014).

678 While predicted GBOs remain rather small compared to other high alpine areas in the world  
679 such as the Himalaya where they frequently exceed  $10^6 \text{ m}^3$  (Linsbauer et al., 2016), their  
680 relevance in terms of hazards sources is high because downstream slopes are generally steep  
681 adjacent valley floors often are densely occupied in the French Alps. Settlements are quite often  
682 right below glacier areas, and mountain flanks are equipped with numerous infrastructures to  
683 host a variety of leisure and tourism activities. Mountain communities may thus be affected by  
684 possible dangerous high-magnitude and cascading processes associated with recently formed  
685 or potential future lakes that can develop in GBOs. Rock/ice avalanches can impact such lakes  
686 or morainic dams can suddenly breach (Allen et al., 2016b, 2016a; Ashraf et al., 2012; Clague  
687 and Evans, 2000; Emmer, 2017; Hubbard et al., 2005; Schaub et al., 2016; Schneider et al.,  
688 2014; Somos-Valenzuela et al., 2016; Worni et al., 2012). A recent example of high-magnitude  
689 chain-reaction hazards in the European Alps was associated to the Piz Cengalo rock avalanche  
690 in 2017 ( $3 \text{ Mm}^3$ , southern Swiss Alps), which provoked a debris flow that killed 8 people on its  
691 way and damaged about 100 infrastructures in the village of Bondo. This hazards chain did not

692 involve any lake but was certainly favoured by the water retained in glacial sediments (Walter  
693 et al., 2020), and thus highlights how damaging such hazards could be, notably if the mass  
694 movement hits an open water body. Possible hazard issues also have to be analysed in the light  
695 of recent studies demonstrating an accentuated glacial retreat in response to summer heat waves  
696 (Rabatel et al., 2013), which also provoke permafrost degradation and enhanced rockfall  
697 activity (Ravanel and Deline, 2011; Ravanel et al., 2010; 2017; Walter et al., 2020). Therefore,  
698 glacial lakes located at the foot of high mountain rock walls subject to debuitressing and/or  
699 permafrost degradation can become evident “hot spots”.

700 In this respect, the Mont Blanc massif appears as the most exposed one with 50% of the most  
701 plausible GBOs, the most voluminous ones (under the Talèfre, Tré la Tête glacier and  
702 Argentière glaciers). Given that the Chamonix valley is densely populated with 8 759  
703 inhabitants (INSEE, 2016) with an high tourism frequentation (12 304 700 overnight stays in  
704 2016 in the *Pays du Mont Blanc*; Savoie Mont Blanc Tourisme, 2017), that the mountain flanks  
705 are roamed by mountaineers, hikers and contemplative tourists (1,619,426 tickets for the  
706 Montenvers train and the Aiguille du Midi cable car; Savoie Mont Blanc Tourisme, 2017), risks  
707 associated to sudden lake draining are exacerbated. Magnin et al. (2020) have already pointed  
708 out potential future lakes located right below high-elevated permafrost rockwalls in the Mont  
709 Blanc massif (the Pélerins or Miage glacier for example) but also suggested possible lakes that  
710 could become future opportunities for water supply (*e.g.* Tour glacier). Hazard potentials would  
711 have to be carefully assessed (GAPHAZ, 2017) in such cases. In addition, these results also  
712 raise questions in terms of attractiveness for tourism related to the perceptions of glacial and  
713 periglacial landscapes (Salim et al., 2019).

714 In the Vanoise massif, despite many predicted GBOs have a rather low level of confidence,  
715 they might be considered as there are also many touristic infrastructures, like mountain huts or  
716 ski resorts. When considering levels of confidence, potential volumes, the presence of steep  
717 slopes and permafrost upstream, and possible vulnerabilities, the Evettes glacier, the Rosolin  
718 glacier and the Epéna glacier (fig. 10) could become hot spots as they are located right below  
719 the 700-m-high north face of the Grande Casse (3855 m a.s.l.), which is still affected by  
720 permafrost according to the map from Boeckli et al. (2012) and feed the Doron de Champagny,  
721 that reach the touristic village of Champagny-en-Vanoise about 10 km below. Historically,  
722 Champagny-en-Vanoise has already known major GLOF events, notably in 1818 when the  
723 Glière lake became obstructed by the l'Epéna glacier tongue and suddenly discharged 3.7 Mm<sup>3</sup>  
724 in the Doron de Champagny and caused severe damages (Mougin, 2001). More recently, the

725 lake that formed at the snout of the Patinoire glacier (fig. 7K) already outburst in 1964 because  
726 of the impact of an ice fall from the Vallonet glacier, causing an impact wave which triggered  
727 breaching of its morainic dam. The village of Pralognan-la-Vanoise was partly flooded and  
728 bridges and cars were swept up. At present, the Vallonet glacier has vanished but this lake  
729 remains a possible hot spot as it is surrounded by steep slopes.

730

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

735 *Fig. 10 – Exemple de hot spot possible dans le massif de la Vanoise : le glacier de l’Epena et le glacier*  
736 *de Rosolin. (Zones rouges : pente > 30° ; zones bleues : indice de permafrost > 0.5 (Marcer et al.,*  
737 *2017) pour les pentes <35° indice de permafrost > 0.5 (Boeckli et al. 2012) pour les pentes >35° ;*  
738 *image de Google Earth).*

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

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

743

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

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

757



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

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

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

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

770

## 771 **6. Conclusions et perspectives**

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

778 • The predicted GBOs quite reliably indicate flat to markedly overdeepened parts of  
779 glacier beds, the latter especially – but not exclusively – where morphological  
780 indications are strong. Artefacts and failures must be expected at wedge-type ice  
781 margins of rapidly retreating to even decaying small glaciers and at heavily debris  
782 covered glacier tongues where sediment input is high. However, no significant water  
783 body was found where no GBO was predicted.

784 • 139 GBOs are predicted (after sorting out GlabTop and GlabTop 2 output to avoid  
785 duplicated GBOs) and represent a total surface area of 9.48 km<sup>2</sup> (3.5% of the glacier  
786 surface area), about which 50% are in the Mont Blanc massif (40 GBOs), 30% in the  
787 Vanoise massif (60 GBOs) and 16% in the Ecrins massif (30 GBOs). They also  
788 represent a total volume of 217.4 Mm<sup>3</sup>, 67% of which is in the Mont Blanc massif, 19%  
789 in the Vanoise massif and 9% in the Ecrins massif.

790 • Their altitudinal distribution is directly related to the one of the related glaciers with the  
791 least elevated GBOs predicted in the Mont Blanc massif were glaciers reach the lowest

792 elevation. However, the Ecrins massif gathers half of its predicted GBOs between 2200  
793 and 2500 m a.s.l., while this lower half is more stretched for the other massifs (2500 –  
794 3000 m a.s.l. for the Vanoise and 1750-2750 for the Mont Blanc massif). Only one  
795 single GBO is predicted > 3500 m a.s.l.

- 796 • Among the 139 predicted GBOs, 59 have a medium, high and very high confidence ( $\geq$   
797  $3/5$ ), which means that they are they are likely to exist, and 50 % of them are in the  
798 Mont Blanc massif. However, 73 % of GBOs with a low and very low confidence ( $\leq$   
799  $1/5$ ) are in the Vanoise massif which hosts many ice-cap like glaciers with firm divides  
800 which are not easily treated with the here-applied approaches. Larger and deeper GBOs  
801 all have a medium to high level of confidence.
- 802 • The larger, deeper and most voluminous GBOs are predicted in the Mont Blanc massif,  
803 the deepest one being at the Argentière glacier (146 m) and the most voluminous one at  
804 the Talèfre glacier (24.8 Mm<sup>3</sup>), both characterised by high levels of confidence.
- 805 • 17 predicted GBOs (> 0.01 km<sup>2</sup>) at recently deglaciated forefields have already yielded  
806 a water body. The confidence levels of the predictions were generally high for these  
807 cases. In 15 cases of GBO predictions at generally low confidence levels, dry conditions  
808 are combined with the absence of marked bedrock threshold, relatively steep slopes >  
809 10-15°, or dynamic sediment infilling. Additionally, 2 lakes already > 0,01 km<sup>2</sup> or that  
810 could reach that size in the future have started to form where GBOs < 0,01 km were  
811 predicted.
- 812 • In addition to the GlabTop results, 58 GBOs have been visually detected by analysing  
813 glacier morphologies, among which 30 are in the Vanoise massif, 15 in the Mont Blanc  
814 massif, 12 in the Ecrins massif and 1 in the Grandes Rousses massif. 4 of them are >  
815 3500 m a.s.l.

816 Our study provides key-information about rapidly emerging high-mountain landscapes as a  
817 consequence of glacier retreat to even vanishing. It represents an essential first step for potential  
818 future research, which will constitute a basis of reflection for decision-makers in long-term  
819 planning. Although the predicted depths and volumes of GBOs remain uncertain, their location  
820 and level of confidence are relevant to anticipate potential future lake formation and to highlight  
821 possible hot spots in terms of GLOF hazards, but also to recognize opportunities related to water  
822 resources, hydropower production and tourism in the French Alps. The resulting inventory of  
823 potential future lakes especially indicates where more detailed investigation should be  
824 conducted in areas of interest. This could involve modelling of glacier retreat to assess the time

825 range under which potential lakes could form, geophysical soundings to assess GBOs  
826 morphometrics, or numerical model calculations of potentially involved process chains  
827 following rock/ice avalanches and related displacement/flood waves or debris flows to assess  
828 possible impacts, hazards and risks to humans and their infrastructure.

829

### 830 **Acknowledgment**

831 The authors acknowledge Horst Machguth (Department of Geosciences, University of  
832 Fribourg, Switzerland) for modelling glacier ice thickness distribution with GlabTop2. The  
833 study received no financial support for this research.

834

### 835 **References:**

836 **Allen, S.K., Linsbauer, A., Randhawa, S.S., Huggel, C., Rana, P. and Kumari, A. (2016a)**  
837 – Glacial lake outburst flood risk in Himachal Pradesh, India: an integrative and anticipatory  
838 approach considering current and future threats, *Nat Hazards*, 84(3), 1741–1763.

839 DOI:10.1007/s11069-016-2511-x

840 **Allen, S.K., Rastner, P., Arora, M., Huggel, C. and Stoffel, M. (2016b)** – Lake outburst and  
841 debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic  
842 predisposition, *Landslides*, 13(6), 1479–1491.

843 DOI:10.1007/s10346-015-0584-3

844 **Ashraf, A., Naz, R. and Roohi, R. (2012)**: Glacial lake outburst flood hazards in Hindukush,  
845 Karakoram and Himalayan Ranges of Pakistan: implications and risk analysis, *Geomatics,*  
846 *Natural Hazards and Risk*, 3(2), 113–132.

847 DOI:10.1080/19475705.2011.615344

848 **Byers, A. C., Rounce, D. R., Shugar, D. H., Lala, J. M., Byers, E. A., & Regmi, D. (2018)**  
849 – A rockfall-induced glacial lake outburst flood, Upper Barun Valley, Nepal. *Landslides*.

850 DOI: <https://doi.org/10.1007/s10346-018-1079-9>

851 **Carey, M. (2005)** – Living and dying with glaciers: people's historical vulnerability to  
852 avalanches and outburst floods in Peru, *Global and Planetary Change*, 47(2), 122–134.

853 DOI: 10.1016/j.gloplacha.2004.10.007

854 **Carey, M., Huggel, C., Bury, J., Portocarrero, C. and Haerberli, W. (2012)** – An integrated  
855 socio-environmental framework for glacier hazard management and climate change adaptation:  
856 lessons from Lake 513, Cordillera Blanca, Peru. *Climatic Change* 112, 3, 733–767.

857 DOI:10.1007/s10584-011-0249-8

858 **Clague, J.J. and Evans, S.G. (2000)** – A review of catastrophic drainage of moraine-dammed  
859 lakes in British Columbia, *Quaternary Science Reviews*, 19(17), 1763–1783.  
860 DOI: [10.1016/S0277-3791\(00\)00090-1](https://doi.org/10.1016/S0277-3791(00)00090-1)

861 **Colonia, D., Torres, J., Haeberli, W., Schauwecker, S., Braendle, E., Giraldez, C., &**  
862 **Cochachin, A. (2017)** – Compiling an Inventory of Glacier-Bed Overdeepenings and Potential  
863 New Lakes in De-Glaciating Areas of the Peruvian Andes : Approach, First Results, and  
864 Perspectives for Adaptation to Climate Change. *Water*, 9(5), 336.  
865 DOI: <https://doi.org/10.3390/w9050336>

866 **Deline, P., Gardent, M., Magnin, F., & Ravanel, L. (2012)** – The morphodynamics of the  
867 mont blanc massif in a changing cryosphere : A comprehensive review. *Geografiska Annaler :*  
868 *Series A, Physical Geography*, 94(2), 265-283.  
869 DOI: <https://doi.org/10.1111/j.1468-0459.2012.00467.x>

870 **Drenkhan, F., Guardamino, L., Huggel, C. and Frey, H. (2018)** – Current and future glacier  
871 and lake assessment in the deglaciating Vilcanota-Urubamba basin, Peruvian Andes, *Global*  
872 *and Planetary Change*, 169, 105–118.  
873 DOI: [10.1016/j.gloplacha.2018.07.005](https://doi.org/10.1016/j.gloplacha.2018.07.005)

874 **Einhorn, B., Eckert, N., Chaix, C., Ravanel, L., Deline, P., Gardent, M., Boudières, V.,**  
875 **Richard, D., Vengeon, J.-M., Giraud, G., & Schoeneich, P. (2015)** – Changements  
876 climatiques et risques naturels dans les Alpes. Impacts observés et potentiels sur les systèmes  
877 physiques et socio-économiques. *Journal of Alpine Research | Revue de géographie alpine*,  
878 103-2.  
879 DOI: <https://doi.org/10.4000/rga.2829>

880 **Emmer, A. (2017)** – Glacier Retreat and Glacial Lake Outburst Floods (GLOFs), Oxford  
881 *Research Encyclopedia of Natural Hazard Science*.  
882 DOI: [10.1093/acrefore/9780199389407.013.275](https://doi.org/10.1093/acrefore/9780199389407.013.275)

883 **Farinotti, D., Brinkerhoff, D.J., Clarke, G.K.C., Fürst, J.J., Frey, H., Gantayat, P., Gillet-**  
884 **Chalet, F., Girard, C., Huss, M., Leclercq, P.W., Linsbauer, A., Machguth, H., Martin,**  
885 **C., Maussion, F., Morlighem, M., Mosbeux, C., Pandit, A., Portmann, A., Rabatel, A.,**  
886 **Ramsankaran, R., Reerink, T.J., Sanchez, O., Stentoft, P.A., Singh Kumari, S., Pvan Pelt,**  
887 **W.J.J., Anderson, B., Benham, T., Binder, D., Dowdeswell, J.A., Fischer, A.Helfricht, K.,**  
888 **Kutuzov, S., Lavrentiev, I., McNabb, R., Gudmundsson, G.H., Li, H., Andreassen, L.M.**  
889 **(2017)** – How accurate are estimates of glacier ice thickness? Results from ITMIX, the Ice  
890 Thickness Models Intercomparison eXperiment. *The Cryosphere*, 11(2), 949-970.  
891 DOI: <https://doi.org/10.5194/tc-11-949-2017>

- 892 **Farinotti, D., Huss, M., Bauder, A., & Funk, M. (2009)** – An estimate of the glacier ice  
893 volume in the Swiss Alps. *Global and Planetary Change*, 68(3), 225-231.  
894 DOI: <https://doi.org/10.1016/j.gloplacha.2009.05.004>
- 895 **Farinotti, D., Huss, M., Fürst, J. J., Landmann, J., Machguth, H., Maussion, F., & Pandit,  
896 A. (2019)** – A consensus estimate for the ice thickness distribution of all glaciers on Earth.  
897 *Nature Geoscience*, 12(3), 168-173.  
898 DOI: <https://doi.org/10.1038/s41561-019-0300-3>
- 899 **Frey, H., Haerberli, W., Linsbauer, A., Huggel, C., & Paul, F. (2010)** – A multi-level strategy  
900 for anticipating future glacier lake formation and associated hazard potentials. *Natural Hazards  
901 and Earth System Sciences*, 10(2), 339-352.  
902 DOI: <https://doi.org/10.5194/nhess-10-339-2010>
- 903 **Frey, H., Machguth, H., Huss, M., Huggel, C., Bajracharya, S., Bolch, T., Kulkarni, A.,  
904 Linsbauer, A., Salzmann, N., & Stoffel, M. (2014)** – Estimating the volume of glaciers in the  
905 Himalayan–Karakoram region using different methods. *The Cryosphere*, 8(6).  
906 DOI: <https://doc.rero.ch/record/234306>
- 907 **GAPHAZ. (2017)** – Assessment of Glacier and Permafrost Hazards in Mountain Regions -  
908 Technical Guidance Document, International Association of Cryospheric Sciences (IASC) and  
909 the International Permafrost Association (IPA), Zurich, Switzerland / Lima, Peru.
- 910 **Gardent, M. (2014)** – Inventaire et retrait des glaciers dans les alpes françaises depuis la fin  
911 du Petit Age Glaciaire. Thèse de doctorat, Université Savoie Mont-Blanc, 455 p.
- 912 **Gardent, M., Rabatel, A., Dedieu, J.-P., & Deline, P. (2014)** – Multitemporal glacier  
913 inventory of the French Alps from the late 1960s to the late 2000s. *Global and Planetary  
914 Change*, 120, 24-37.  
915 DOI: <https://doi.org/10.1016/j.gloplacha.2014.05.004>
- 916 **Guardamino, L., Haerberli, W., Muñoz, R., Drenkhan, F., Tacsí, A. and Cochaching, A.  
917 (2019)** – Proyección de lagunas Futuras en las Cordilleras Glaciares del Perú. *Ministra de  
918 Agricultura y Riego, Autoridad Nacional del Agua, Dirección de Calidad y Evaluación de  
919 Calidad de Recursos Hídricos, Área de Evaluación de Glaciares y Lagunas.*  
920 <http://repositorio.ana.gob.pe/handle/ANA/3597>
- 921 **Haerberli, W. (2017)** – Integrative modelling and managing new landscapes and environments  
922 in de-glaciating mountain ranges: An emerging trans-disciplinary research field, *Forestry  
923 Research and Engineering: International Journal*, 1(1).  
924 DOI: [10.15406/freij.2017.01.00005](https://doi.org/10.15406/freij.2017.01.00005)
- 925 **Haerberli, W., Buetler, M., Huggel, C., Lehmann Friedli, T., Schaub, Y., & Schleiss, A.**

926 **(2016)** – New lakes in deglaciating high-mountain regions – opportunities and risks.  
927 ResearchGate, 2(139), 201-214.  
928 DOI: <http://dx.doi.org/10.1007/s10584-016-1771-5>

929 **Haerberli, W., Kääh, A., Mühl, D. V., & Teyssere, P. (2001)** – Prevention of outburst floods  
930 from periglacial lakes at Grubengletscher, Valais, Swiss Alps. *Journal of Glaciology*, 47(156),  
931 111-122.  
932 DOI: <https://doi.org/10.3189/172756501781832575>

933 **Hubbard, B., Heald, A., Reynolds, J. M., Quincey, D., Richardson, S. D., Luyo, M. Z.,**  
934 **Portilla, N. S. and Hambrey, M. J. (2005)** – Impact of a rock avalanche on a moraine-dammed  
935 proglacial lake: Laguna Safuna Alta, Cordillera Blanca, Peru, *Earth Surface Processes and*  
936 *Landforms*, 30(10), 1251–1264.  
937 DOI: [10.1002/esp.1198](https://doi.org/10.1002/esp.1198)

938 **Huss, M. (2012)** – Extrapolating glacier mass balance to the mountain range scale : The  
939 European Alps 1900–2100. *The Cryosphere Discuss.*, 6, 1117-1156.  
940 DOI: <http://dx.doi.org/10.5194/tcd-6-1117-2012>

941 **INSEE. (2019)** – Comparateur de territoire – Commune de Chamonix-Mont-Blanc (74056) |  
942 Insee. Comparateur de territoire.  
943 DOI: <https://www.insee.fr/fr/statistiques/1405599?geo=COM-74056>

944 **IPCC. (2019)** – Special Report on the Ocean and Cryosphere in a Changing Climate. In:  
945 Chapter 2: High Mountain Areas, In press

946 **Kapitsa, V., Shahgedanova, M., Machguth, H., Severskiy, I., & Medeu, A. (2017)** –  
947 Assessment of evolution and risks of glacier lake outbursts in the Djungarskiy Alatau, Central  
948 Asia, using Landsat imagery and glacier bed topography modelling. *Natural Hazards and Earth*  
949 *System Sciences*, 17(10), 1837-1856.  
950 DOI: <https://doi.org/10.5194/nhess-17-1837-2017>

951 **Le Meur, E. L. and Vincent, C. (2003)** – A two-dimensional shallow ice-flow model of  
952 Glacier de Saint-Sorlin, France, *Journal of Glaciology*, 49(167), 527–538.  
953 DOI: [10.3189/172756503781830421](https://doi.org/10.3189/172756503781830421)

954 **Linsbauer, A., Frey, H., Haerberli, W., Machguth, H., Azam, M. F., & Allen, S. (2016)** –  
955 Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya  
956 – Karakoram region. *Annals of Glaciology*, 57(71), 119-130.  
957 DOI: <https://doi.org/10.3189/2016AoG71A627>

958 **Linsbauer, A., Paul, F., Hoelzle, M., Frey, H. and Haerberli, W. (2009)** – The Swiss Alps  
959 without glaciers – a GIS-based modelling approach for reconstruction of glacier beds.

- 960 Proceedings of Geomorphometry 2009. Zurich, Switzerland, 243-247  
961 DOI: [10.5167/uzh-27834](https://doi.org/10.5167/uzh-27834)
- 962 **Linsbauer, A., Paul, F., & Haeberli, W. (2012)** – Modelling glacier thickness distribution and  
963 bed topography over entire mountain ranges with GlabTop : Application of a fast and robust  
964 approach. *Journal of Geophysical Research: Earth Surface*, 117(F3), 17.  
965 DOI: <https://doi.org/10.1029/2011JF002313>
- 966 **Magnin, F., Josnin, J.-Y., Ravanel, L., Pergaud, J., Pohl, B. and Deline, P. (2017)** –  
967 Modelling rock wall permafrost degradation in the Mont Blanc massif from the LIA to the end  
968 of the 21st century, *The Cryosphere*, 11(4), 1813–1834.  
969 DOI: <https://doi.org/10.5194/tc-11-1813-2017>
- 970 **Magnin, F., Haeberli, W., Linsbauer, A., Deline, P. and Ravanel, L. (2020)** – Estimating  
971 glacier-bed overdeepenings as possible sites of future lakes in the de-glaciating Mont Blanc  
972 massif (Western European Alps), *Geomorphology*, 350, 106913.  
973 DOI: [10.1016/j.geomorph.2019.106913](https://doi.org/10.1016/j.geomorph.2019.106913),
- 974 **Marcet, M., Bodin, X., Brenning, A., Schoeneich, P., Charvet, R., & Gottardi, F. (2017)** –  
975 Permafrost Favorability Index : Spatial Modeling in the French Alps Using a Rock Glacier  
976 Inventory. *Frontiers in Earth Science*, 5.  
977 DOI: <https://doi.org/10.3389/feart.2017.00105>
- 978 **Mougin, P. (2001)** – Les torrents de la Savoie, Eds. La Fontaine de Siloé, 1251 pp
- 979 **Paul, F., & Linsbauer, A. (2012)** – Modeling of glacier bed topography from glacier outlines,  
980 central branch lines, and a DEM. *International Journal of Geographical Information Science*,  
981 26(7), 1173-1190.  
982 DOI: <https://doi.org/10.1080/13658816.2011.627859>
- 983 **PERMOS. (2019)** – Permafrost in Switzerland, 2014/2015 to 2017/2018, Commission of the  
984 Swiss Academy of Sciences. [online].  
985 DOI: [10.13093/permos-rep-2019-16-19](https://doi.org/10.13093/permos-rep-2019-16-19)
- 986 **Purdie, H. (2013)** – Glacier Retreat and Tourism : Insights from New Zealand. *Mountain*  
987 *Research and Development*, 33(4), 463-472.  
988 DOI: <https://doi.org/10.1659/MRD-JOURNAL-D-12-00073.1>
- 989 **Rabatel, A., Letréguilly, A., Dedieu, J. P., & Eckert, N. (2013)** – Changes in glacier  
990 equilibrium-line altitude in the western Alps from 1984 to 2010 : Evaluation by remote sensing  
991 and modeling of the morpho-topographic and climate controls. *The Cryosphere*, 7(5),  
992 1455-1471.  
993 DOI: <https://doi.org/10.5194/tc-7-1455-2013>

994 **Rabatel, Antoine, Sanchez, O., Vincent, C., & Six, D. (2018)** – Estimation of Glacier  
995 Thickness From Surface Mass Balance and Ice Flow Velocities : A Case Study on Argentière  
996 Glacier, France. *Frontiers in Earth Science*, 6.  
997 DOI: <https://doi.org/10.3389/feart.2018.00112>

998 **Ravel, L., Magnin, F., & Deline, P. (2017)** – Impacts of the 2003 and 2015 summer  
999 heatwaves on permafrost-affected rock-walls in the Mont Blanc massif. *Science of The Total*  
1000 *Environment*, 609, 132-143.  
1001 DOI: <https://doi.org/10.1016/j.scitotenv.2017.07.055>

1002 **Ravel, Ludovic, Allignol, F., Deline, P., Gruber, S., & Ravello, M. (2010)** – Rock falls in  
1003 the Mont Blanc Massif in 2007 and 2008. *Landslides*, 7(4), 493-501.  
1004 DOI: <https://doi.org/10.1007/s10346-010-0206-z>

1005 **Ravel, Ludovic, & Deline, P. (2011)** – Climate influence on rockfalls in high-Alpine steep  
1006 rockwalls : The north side of the Aiguilles de Chamonix (Mont Blanc massif) since the end of  
1007 the ‘Little Ice Age’. *The Holocene*, 21(2), 357-365.  
1008 DOI: <https://doi.org/10.1177/0959683610374887>

1009 **Salim, E., Mourey, J., Ravel, L., Picco, P., & Gauchon, C. (2019)** – Mountain guides  
1010 facing the effects of climate change. What perceptions and adaptation strategies at the foot of  
1011 Mont Blanc? *Journal of Alpine Research | Revue de Géographie Alpine*, 107-4, Article 107-4.  
1012 DOI: <https://doi.org/10.4000/rga.5865>

1013 **Savoie Mont Blanc Tourisme. (2017)** – Chiffres 2017 Savoie Mont Blanc Tourisme (p. 8)  
1014 [Zoom territoire]. Pays du Mont Blanc (non publié)  
1015 DOI: [https://www.ccpmb.fr/uploads/2017/07/Chiffres-2017\\_savoie-mont-blanc-tourisme.pdf](https://www.ccpmb.fr/uploads/2017/07/Chiffres-2017_savoie-mont-blanc-tourisme.pdf)

1016 **Schaub, Y., Huggel, C. and Cochachin, A. (2016)** – Ice-avalanche scenario elaboration and  
1017 uncertainty propagation in numerical simulation of rock-/ice-avalanche-induced impact waves  
1018 at Mount Hualcán and Lake 513, Peru, *Landslides*, 13(6), 1445–1459.  
1019 DOI: [10.1007/s10346-015-0658-2](https://doi.org/10.1007/s10346-015-0658-2)

1020 **Schneider, D., Huggel, C., Cochachin, A., Guillén, S. and García, J. (2014)** – Mapping  
1021 hazards from glacier lake outburst floods based on modelling of process cascades at Lake 513,  
1022 Carhuaz, Peru, *Adv. Geosci.*, 35, 145–155.  
1023 DOI: [10.5194/adgeo-35-145-2014](https://doi.org/10.5194/adgeo-35-145-2014)

1024 **Somos-Valenzuela, M. A., Chisolm, R. E., Rivas, D. S., Portocarrero, C. and McKinney,**  
1025 **D. C. (2016)** – Modelling a glacial lake outburst flood process chain: the case of Lake  
1026 Palcacocha and Huaraz, Peru, *Hydrology and Earth System Sciences*, 20(6), 2519–2543.  
1027 DOI: <https://doi.org/10.5194/hess-20-2519-2016>



- 1028 **Vincent, C., Peyaud, V., Laarman, O., Six, D., Gilbert, A., Gillet-Chaulet, F., Berthier, É.,**  
1029 **Morin, S., Verfaillie, D., Rabatel, A., Jourdain, B., & Bolibar, J. (2019)** – Déclin des deux  
1030 plus grands glaciers des Alpes françaises au cours du XXI<sup>e</sup> siècle : Argentière et Mer de Glace.  
1031 *La Météorologie*, 106, 49.  
1032 DOI: <https://doi.org/10.4267/2042/70369>
- 1033 **Walter, F., Amann, F., Kos, A., Kenner, R., Phillips, M., de Preux, A., Huss, M., Tognacca,**  
1034 **C., Clinton, J., Diehl, T. and Bonanomi, Y. (2020)** – Direct observations of a three million  
1035 cubic meter rock-slope collapse with almost immediate initiation of ensuing debris flows,  
1036 *Geomorphology*, 351, 106933.  
1037 DOI: [10.1016/j.geomorph.2019.106933](https://doi.org/10.1016/j.geomorph.2019.106933)
- 1038 **Worni, R., Stoffel, M., Huggel, C., Volz, C., Casteller, A. and Luckman, B. (2012)** –  
1039 Analysis and dynamic modeling of a moraine failure and glacier lake outburst flood at  
1040 Ventisquero Negro, Patagonian Andes (Argentina), *Journal of Hydrology*, 444–445, 134–145.  
1041 DOI: [10.1016/j.jhydrol.2012.04.013](https://doi.org/10.1016/j.jhydrol.2012.04.013)
- 1042 **Zekollari, H., Huss, M., & Farinotti, D. (2019)** – Modelling the future evolution of glaciers  
1043 in the European Alps under the EURO-CORDEX RCM ensemble. *The Cryosphere*, 13(4),  
1044 1125-1146.  
1045 DOI: <https://doi.org/10.5194/tc-13-1125-2019>
- 1046 **Zemp, M., Haeberli, W., Hoelzle, M., & Paul, F. (2006)** – Alpine glaciers to disappear within  
1047 decades? *Geophysical Research Letters*, 33(13).  
1048 DOI: <https://doi.org/10.1029/2006GL026319>
- 1049 **Zemp, M., Kääb, A., Hoelzle, M., & Haeberli, W. (2005)** – GIS-based modelling of glacial  
1050 sediment balance. 18.  
1051 DOI: <https://doi.org/10.5167/uzh-40580>
- 1052 **Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., Haeberli,**  
1053 **W., Denzinger, F., Ahlstrøm, A. P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L.**  
1054 **N., Cáceres, B. E., Casassa, G., Cobos, G., Dávila, L. R., Granados, H. D., Demuth, M. N.,**  
1055 **Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J. O., Holmlund, P.,**  
1056 **Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V. V., Portocarrero, C. A., Prinz, R.,**  
1057 **Sangewar, C. V., Severskiy, I., Sigurdsson, O., Soruco, A., Usubaliev, R. and Vincent, C.**  
1058 **(2015)** – Historically unprecedented global glacier decline in the early 21st century, *Journal of*  
1059 *Glaciology*, 61(228), 745–762.  
1060 DOI: [10.3189/2015JG15J017](https://doi.org/10.3189/2015JG15J017)