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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*

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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 km²) 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 < 0,01km². 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 km²)*
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 < 0,01km². 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 km³
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 km². The smallest is a glacieret in the Ecrins massif (Bans glacier –
123 0.0015 km²) and the largest is the Mer de Glace in the Mont Blanc massif (30.5 km²). 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 m². 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 ≥ 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 km² with GlabTop and at 0.14 km² 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 Mm³ compared to GlabTop which the third quartile
310 is at 1.7 Mm³. 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 km² with
312 GlabTop and 0.035 km² 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 km^2 , about 3.5% of the glacier surface
350 area. Half of it is in the Mont Blanc massif (4.81 km^2 , 4.7% of the glacier surface area in the
351 Mont Blanc massif), about 29% in the Vanoise massif (2.74 km^2 , 3% of the glacier surface area
352 in Vanoise massif) and 16% in the Ecrins massif (1.56 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 km², 0.52 km² and 0.47 km² respectively. In the Vanoise
365 massif, the two GBOs that would have the largest surface area are under the Arcelin glacier
366 (0.25 km²) and the Evettes glacier (0.21 km²). In the Ecrins massif, the two largest GBOs are
367 both found under the Blanc glacier with a surface area of 0.23 km² and 0.22 km² respectively.
368 Finally, another relatively large GBOs was predicted under the Saint Sorlin glacier with a
369 surface area of 0.25 km² 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 Mm³, 67% of which (145.5 Mm³) is in the
387 Mont Blanc massif, 19% (41.3 Mm³) in the Vanoise massif and 9% (20.6 Mm³) 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 Mm³), the Tré la Tête glacier (22.4 Mm³)
390 and the Argentière glacier (20.7 Mm³). 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 Mm³ and 4.5 Mm³ respectively). In the Ecrins massif, the most voluminous GBOs are under
393 the Glacier Blanc (4 Mm³) and the Arsine Glacier (3.3 Mm³), and are both less voluminous than
394 the one under the Saint Sorlin glacier (Grandes Rousses massif, 9 Mm³).

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 km²; 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 km² ; 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 Mm³) 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 (≤ 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 Pèlerin
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 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 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 Mm³
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 km² (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 Mm³, 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 Mm³), both characterised by high levels of confidence.

805 • 17 predicted GBOs (> 0.01 km²) 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 km² 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

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834

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