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## Sensitivity of Alpine glaciers to anthropogenic atmospheric forcings: case study of the Argentière glacier

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### ► To cite this version:

Léo Clauzel, Adrien Gilbert, Ménégoz Martin, Olivier Gagliardini, Delphine Six, et al.. Sensitivity of Alpine glaciers to anthropogenic atmospheric forcings: case study of the Argentière glacier. 2022. hal-03764448

**HAL Id: hal-03764448**

**<https://hal.science/hal-03764448v1>**

Preprint submitted on 30 Aug 2022

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1           **Sensitivity of Alpine glaciers to anthropogenic atmospheric**  
2           **forcings: case study of the Argentière glacier**

3  
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9  
10 **Key points (140 character par key points, pas d'abréviation, 3 max)**

- 11
- 12 ● Ice flow simulations forced with climate model outputs are used to explore natural and  
13 anthropogenic imprints on the Argentière glacier.
  - 14 ● Statistical downscaling needs to ensure a conservation of the trends and the physical  
15 relationship between temperature and precipitation.
  - 16 ● The anthropogenic imprint on the Argentière glacier mass emerged from internal  
17 variability in 2003, 30 years after that on temperature.
- 18

19 **Key words (6 max)**

20 statistical adjustment - glacier modelling - external climate forcings - detection-attribution - time  
21 of emergence

22  
23 **Abstract (150 words < 150)**

24  
25 This study aims at quantifying the contribution of external climate forcings on the retreat of the  
26 Argentière glacier (Mont-Blanc area). Its evolution is simulated over 1850-2014 following  
27 retrospective scenarios produced with the IPSL-CM6-LR climate model, excluding and  
28 including natural and anthropogenic forcings. These scenarios are statistically adjusted at the  
29 local scale, ensuring a preservation of the long-term trends and a physical consistency  
30 between precipitation and temperature, to finally force an ice flow model coupled with a  
31 surface mass balance scheme. The regional aerosol cooling partly counteracted the  
32 greenhouse gases warming, delaying the time of emergence of anthropogenic signals: The  
33 anthropogenic influences emerged from the natural variability in 1979 for temperature and in  
34 2008 for the mass of the glacier, whereas its snout position in 2014 remains compatible with  
35 natural variability. We found that 66% [20-112%] of the total mass loss in 2014 since 1850  
36 can be attributed to anthropogenic activities.

37  
38 **Plain Language Summary (200 words max sans acronymes)**

39  
40 This work aims at quantifying the anthropogenic imprint on the Argentière glacier with respect  
41 to its changes related to climate natural variability. It is based on a detection-attribution  
42 approach used to produce retrospective ensemble simulations of the climate and the glaciers,  
43 including and excluding greenhouse gases and aerosol forcings over 1850-2014. The time of  
44 emergence of the anthropogenic signal, i.e. the date when it becomes statistically incompatible  
45 with climate internal variability, occurs in 1979 for temperature in the Argentière location, with  
46 a warming reaching 1.35 °C in 2014. It occurs later for the glacier changes, in particular for

47 the snout position that is still compatible with internal variability in 2014. For the glacier mass,  
48 it occurred in 2008, ~30 years after those of the temperature. In 2014, 66% [20-112%] of the  
49 total mass loss since 1850 can be attributed to anthropogenic activities. This result is sensitive  
50 to the internal variability estimate from the climate model, and it should be completed in further  
51 studies including both the cooling of the aerosols when they are located in the atmosphere  
52 and the melt increase when they are deposited onto the snow. This study highlights a  
53 strengthening of the current glacier retreat.

54

## 55 **1. Introduction**

56

57 Mountain glaciers around the world retreated dramatically over the last decades. Apart being  
58 an iconic symbol of the ongoing climate change, this retreat has strong environmental and  
59 societal impacts: over 1971-2018, the mass loss of mountain glaciers is the second contributor  
60 to sea level rise, with a 22% contribution, coming after the 50% related to the thermal  
61 expansion of the ocean and before the 20% explained by the ice caps melting (IPCC, 2021).  
62 The retreat of glaciers is also a threat for water availability in particular where they play the  
63 role of fresh water reservoirs essential for biodiversity and human societies (Kaser et al., 2010;  
64 Milner et al., 2017; Laurent et al., 2020).

65

66 Alpine glacier extensions reached a maxima at the end of the little ice age (LIA; Zumbühl and  
67 Nussbaumer, 2018). The LIA covers approximately 1400-1700, a cold period induced by  
68 strong volcanic activity and a minimum of solar activity (Mann et al., 2009). After the LIA, the  
69 18th century is considered as a temperature constant reference period without any strong  
70 external forcing (Hawkins et al., 2017), whereas low temperature has been observed again  
71 during the period 1800-1850, in relation to volcanic eruptions and changes of solar activity that  
72 favoured large glacier extensions in the Alps (Zumbühl and Nussbaumer, 2018). The retreat  
73 of Alpine glaciers started in 1850, simultaneously with the beginning of anthropogenic  
74 emissions of greenhouse gases (GHGs). The exact causes of this retreat are still debated,  
75 since the temperature increase was relatively small during the end of the XIXth century, and  
76 other factors like decadal variability of precipitation (Vincent et al., 2005) and deposition of  
77 absorbing aerosols on snow (Painter et al., 2013) might have also affected glaciers. Future  
78 glacier projections need to be considered carefully because the glacier sensitivity to external  
79 forcing and climate internal variability is still uncertain (Marzeion et al, 2020).

80

81 Detection-attribution studies have been used to estimate the climate response to external  
82 forcings, using both climate models and observations of surface air temperature. Such studies  
83 typically estimate that the global warming of +1.2°C (+/-0.15°C), observed in 2010-2020 as  
84 compared to the pre-industrial era, can be decomposed in +1.5°C (+/-0.3°C) related to GHGs  
85 and -0.4°C (+/-0.3°C) related to other forcings (Haustein et al., 2017 ; Gillett et al., 2021 ; Ribes  
86 et al., 2021 ; Eyring et al. 2021). These other forcings mainly reflect the effect of anthropogenic  
87 aerosols that cool the atmosphere. Detection-attribution methods allow to highlight the climate  
88 response to external forcings with respect to internal variability. Following such an approach,  
89 Roe et al. (2017; 2021) suggested that 100% of the glacier global mass loss from the pre-  
90 industrial era is explained by anthropogenic forcings. However, such approaches do not allow  
91 to accurately quantify the emergence of the anthropogenic signals at the local scale and  
92 cannot be used to differentiate the role of GHGs and aerosols, because they are based on  
93 idealised depictions of the climate and the glacier systems. More physical approaches are

94 used to quantify separately the natural and anthropogenic imprints on glaciers with global  
95 models (e.g. Marzeion et al., 2014; Maussion et al., 2019) and their contribution to sea level  
96 changes (e.g. Huss and Hock, 2015). These approaches are inevitably strongly idealised for  
97 global applications, in particular because of the complexity of the physical processes at play  
98 that cannot be verified due to the impossibility to get observational data for all the glaciers on  
99 the Earth. To be fully reliable, physical approaches would require: (1) a realistic atmospheric  
100 forcing, that is generally obtained from the statistical adjustment of atmosphere-ocean general  
101 circulation models (AOGCMs) outputs, used to extrapolate the local observations when they  
102 are not available. Several adjustment techniques has been proposed to ensure a conservation  
103 of the trends and the interannual variability of atmospheric variables, as well as a physical  
104 consistency between themselves (Latombe et al., 2018; Luo et al., 2018, Gutierrez et al., 2019,  
105 Vaittinada et al., 2021); (2) a model allowing to simulate the 3D glacier flow and its geometry  
106 evolution, that needs local observations for calibration; (3) an adequate initialisation of the  
107 glacier model, a crucial step since climate internal variability might induce strong decadal  
108 variations of glaciers, even in a non-perturbed climate.

109

110 The aim of this study is to investigate the drivers of the Argentière glacier changes in the Alpine  
111 area over 1850-2014 by quantifying separately the impacts of GHGs, aerosols and climate  
112 internal variability. After a presentation of the data and the methods in Section 2, the results  
113 are described in Section 3, before a discussion and a conclusion in Section 4.

114

## 115 **2. Data and Methods**

116

### 117 **2.1 Local observations and climate forcing**

118

119 Located in the Mont-Blanc massif, the Argentière Glacier (45°57'N, 6°58'E) is the second  
120 largest glacier in the French Alps, covering an area of 11.3 km<sup>2</sup> in 2019, extended over ~10km  
121 from 1550 to 3500 m a.s.l. (Six and Vincent, 2014). Stake measurements, geodetic  
122 observations, GPS survey and radar observations (Rabatel et al., 2018; Vincent et al, 2009)  
123 are used to monitor this glacier within the framework of the GLACIOCLIM observatory  
124 (<https://glacioclim.osug.fr/>).

125

126 Atmospheric data is extracted here from experiments produced with the IPSL-CM6A-LR  
127 AOGCM (Boucher et al., 2020), in the context of the Detection and Attribution Model  
128 Intercomparison Project (DAMIP, Gillett et al., 2016) panel of CMIP6 (Coupled Model  
129 Intercomparison Phase 6). DAMIP aims at quantifying separately the imprint of natural and  
130 anthropogenic external climate forcing. We use here a subset of the IPSL-CM6A-LR  
131 experiments: (i) a 10-member historical experiment (*hist*) that includes all natural and  
132 anthropogenic forcings and 3 sets of 6-member experiments, including (ii) only the natural  
133 (*nat*), only the anthropogenic aerosol (*aer*) and only the anthropogenic greenhouse gas (*ghg*)  
134 forcings. The *hist* simulations also include the effect of changing stratospheric ozone and land  
135 use, but these two effects should only play a minor role at the local scale in the Mont-Blanc  
136 area. The natural external forcings designate here the volcanic and the solar activities. The  
137 simulations are available over 1850-2014 and member-experiments differ between  
138 themselves only by their initial conditions that have been sampled from a 1000-year pre-  
139 industrial control experiment. Corresponding members from one experiment to another one  
140 have the same initial conditions. Hereafter, the internal variability designates the variability

141 sampled with the different ensemble members. The SAFRAN reanalysis available for the  
142 different French Alpine regions with a 300m vertical resolution (Vernay et al., 2022) is used  
143 here to statistically adjust the AOGCM data extracted from the gridpoint containing the  
144 Argentière Glacier.

145

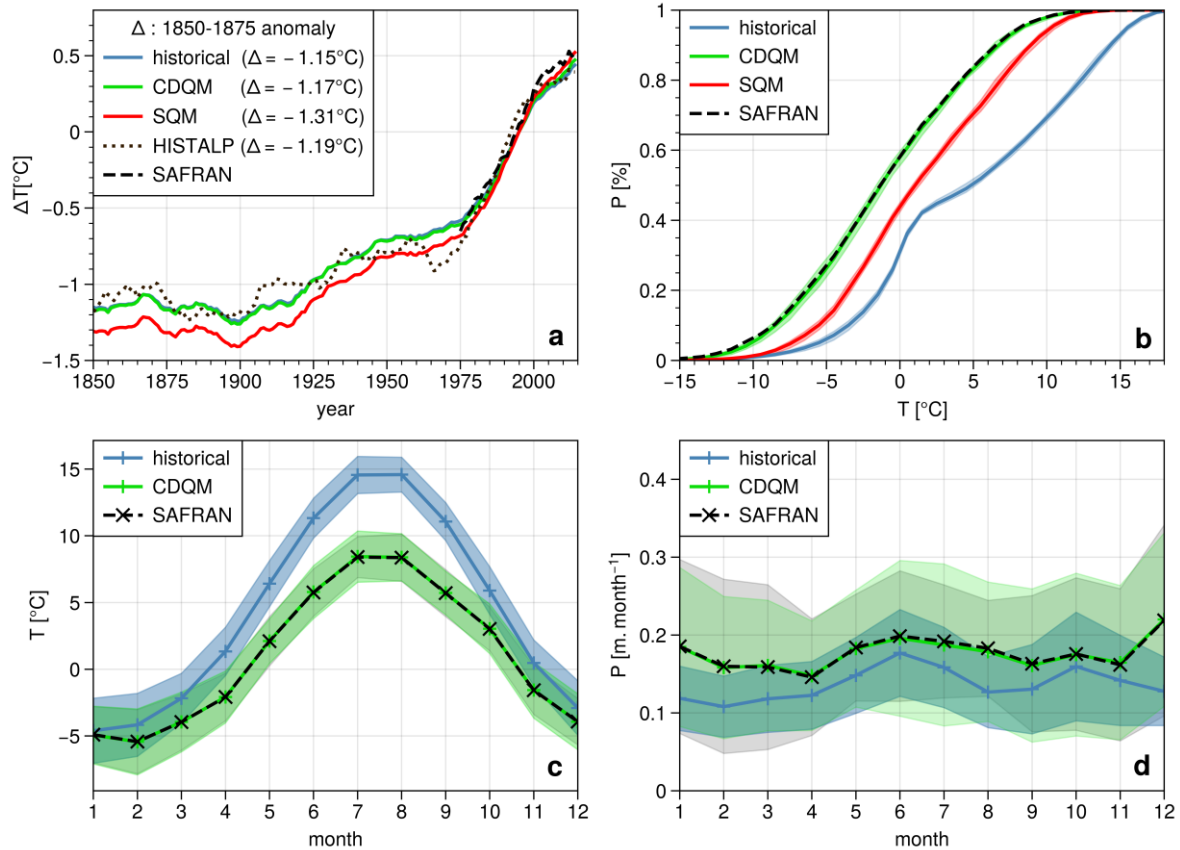
## 146 **2.2 Statistical downscaling of climate data**

147 The daily AOGCM temperature and precipitation are simultaneously bias corrected and  
148 downscaled with a monthly statistical adjustment, considering the difference between the *hist*  
149 experiment and the SAFRAN reference at 2400m a.s.l., i.e. close to the glacier mean altitude.  
150 The adjustment is calibrated over 1975-2014 with the 10 *hist* members and is then applied to  
151 the whole set of ensemble experiments *hist*, *nat*, *aer* and *ghg*, considering the correction  
152 stationary over 1850-2014.

153 The simple quantile mapping (SQM, Panofsky and Brier, 1968) is used here to fit the  
154 cumulative distributive function of the model variables on the observation ones. However, this  
155 method induces a spurious amplification of the long term temperature trend (Figure 1a) and  
156 an underestimation of snow accumulation as the precipitation distribution over the temperature  
157 1°C-width bins is shifted to warmer days (Figure 1b). To overcome these issues, the Quantile  
158 Delta Mapping (QDM, Cannon et al., 2015), that ensures a conservation of trends, is first used  
159 to adjust temperature. The 2D-variable successive conditional approach of Piani and Haerter  
160 (2012) is then followed by applying the SQM methods for precipitation separately for 5  
161 quantiles of temperature, to keep the physical consistency between the two variables. The  
162 temperature-quantile bins are defined on 40-year moving sub-periods to avoid any impact of  
163 temperature trends on the precipitation adjustment. This combination of these two statistical  
164 adjustments is defined here as the Coupled Delta Quantile Mapping (CDQM).

165 The CDQM method ensures a conservation of the temperature trend simulated with the  
166 AOGCM that is in accordance with the HISTALP reconstruction (Böhm et al., 2010; Figure  
167 1a), a physical precipitation-temperature relationship consistent with the SAFRAN reanalysis  
168 (Figure 1b) as well as realistic seasonal cycles, daily and interannual variability for these two  
169 variables (Figure S1).

170



**Figure 1.** (a) 30-year running mean temperature anomaly with respect to the 1975-2014 mean, averaged over members. Blue line is the historical simulations, red and green lines are respectively their SQM and CDQM adjustments. The HISTALP data is denoted with the black dotted line and SAFRAN with the dashed line. The  $\Delta$  given in brackets is the difference between the 1850-1875 and the 1975-2014 means; (b) cumulative distribution function of precipitation over  $1^\circ\text{C}$ -wide bins of temperature, averaged over members ; (c) cumulated SMB and (d) length change from 1850. Dashed lines are individual members and solid lines are the 10-member mean in (cd). The glaciological simulation forced with SAFRAN corresponds to the black line, the GLACIOCLIM in-situ data appears in brown, the estimate from Zemp et al. (2019) in cyan, geodetic data are denoted with blue crosses and proxies with the black points. Proxies are derived from moraine isotopic analysis (Protin et al., 2019).

171

## 172 2.3 Glaciological model

### 173 2.3.1 Ice flow model

174 The glacier response to climate forcing is simulated using a coupled surface mass balance -  
 175 3D ice flow model based on the Elmer/Ice finite element code (Gagliardini et al., 2013). The  
 176 ice flow model solves the Stokes equations adopting Glen's flow law for viscous isotropic  
 177 temperate ice (Cuffey & Paterson, 2010). The basal boundary condition is given by a  
 178 Weertman-type friction law (Weertman, 1957):

$$179 A_s \tau_b^m = u_b \quad (1)$$

180 where  $\tau_b$  is the basal shear stress (MPa),  $u_b$  the sliding velocity ( $m yr^{-1}$ ),  $A_s$  the friction  
 181 coefficient ( $m yr^{-1} MPa^{-m}$ ) and  $m$  an exponent fixed to  $m = 3$  for Argentière glacier (Gimbert et  
 182 al., 2021). The friction coefficient  $A_s$  is assumed to be uniform and constant in time. The  
 183 evolution of the ice thickness is computed at a  $1/20$  year time step ( $\sim 18$  days) through the

184 resolution of the free surface equation for the given surface mass balance and ice velocity  
185 field (Gagliardini et al., 2013).

## 186 **2.3.2 Surface Mass Balance scheme**

187 The mass balance scheme computes the daily distributed surface mass balance (SMB) from  
188 daily precipitation and temperature which is then cumulated over the 1/20 year simulation  
189 timestep to force the ice flow model. The local net daily SMB ( $m \text{ w.eq. } d^{-1}$ ) is determined by:

$$190 \quad \quad \quad SMB = A - M \quad (2)$$

191 where  $A$  and  $M$  are respectively the local daily snow accumulation and surface melting  
192 ( $m \text{ w.eq. } d^{-1}$ ). The amount of melt  $M$  is computed from the available energy for melt following  
193 Oerlemans (2001):

$$194 \quad \quad \quad Q_m = (1 - \alpha)rI_{pot} + k_1T + k_0 \quad (3)$$

195 where  $\alpha$  is the local surface albedo,  $I_{pot}$  is the potential incoming short-wave radiation (Hock,  
196 1999),  $r$  a corrective factor and  $k_1T + k_0$  is the sum of the long-wave radiation balance and  
197 the turbulent heat exchange linearized around the melting point with  $k_0$  and  $k_1$  as constant  
198 parameters, and  $T$  the air temperature. If  $Q_m$  is positive, the melt rate is obtained with the  
199 latent heat of fusion  $L$ :

$$200 \quad \quad \quad M = Q_m / (L \times \rho_{water}) \quad (4)$$

201 The local surface albedo is estimated from the state of the surface that can be either snow or  
202 ice. Snow and firn thickness evolution is computed at daily time step to determine if  $\alpha = \alpha_{ice}$   
203 or  $\alpha = \alpha_{snow}$  (Gilbert et al., 2020). The local snow accumulation  $A$  is determined from local  
204 daily precipitation according to a snow/rain temperature threshold fixed to  $1^\circ\text{C}$ .

205 Temperature and precipitation data provided at 2400m are distributed to the glacier surface  
206 according to altitudinal lapse rates such as:

$$207 \quad \quad \quad T(z, t) = T_{ref}(t) + \frac{dT}{dz}(z - z_{ref}) \quad (5)$$

$$208 \quad \quad \quad P(x, y, z, t) = M_a(x, y) P_{ref}(t) \left(1 + P_z(z - z_{ref})\right) \quad (6)$$

209 where  $z$  is the elevation of the surface ( $m$ ),  $T_{ref}(t)$  and  $P_{ref}(t)$  are air temperature ( $^\circ\text{C}$ ) and  
210 precipitation ( $m \text{ w.eq.}$ ) at the elevation  $z_{ref} = 2400m$ ,  $\frac{dT}{dz}$  is the temperature lapse rate ( $^\circ\text{C } m^{-1}$ ),  
211  $P_z$  is the precipitation lapse rate and  $M_a(x, y)$  is a spatial correction factor for precipitation  
212 (Table S1).

213

214

## 215 **2.4 Modelling strategy**

216

### 217 **2.4.1 Model calibration**

218

219 In-situ stake measurement of seasonal mass balance performed since 1975 combined to  
220 SAFRAN temperature and precipitation are used to constrain the SMB scheme. The extensive  
221 monitoring of the glacier over a long period allowed a good calibration of the multiple

222 parameters. The SMB scheme is calibrated on a fixed surface topography (1998) such that  
223 the ice flow model is not needed for this step. We verify a posteriori that the SMB remains in  
224 good accordance with the observations when the model is coupled with the ice flow model.  
225 Precipitation correction factor and lapse rate were first calibrated using winter SMB data in  
226 which little melting happened. The observed SMB altitude dependency strongly constraints  
227  $k_1$ ,  $\alpha_{ice}$  and  $\alpha_{snow}$  whereas the total mass change over the whole measurement period  
228 constraints  $r$  and  $k_0$ . The adopted model parameters values are summarised in Table S1.

229

## 230 **2.4.2 Initial state and spin up**

231

232 The 1820 steady-state glacier geometry is obtained by running the SMB scheme coupled to  
233 the ice flow model forced with the 1975-2015 SAFRAN data, assuming a shift of temperature  
234  $\Delta T_0$  and supposing unchanged precipitation rates. A value of  $-1.30^\circ\text{C}$  for  $\Delta T_0$  is required to  
235 obtain a glacier length that matches the 1820 moraine observation, a period when the glacier  
236 was supposed to be in equilibrium with the climate for several decades (Protin et al., 2019). A  
237 30-year spin up over 1820-1850 is then performed separately for the 10 members, allowing to  
238 adjust the glacier shape to the climate internal variability that might induce large interannual  
239 to decadal changes of temperature and precipitation. These spin-ups are forced with the  
240 statistically adjusted atmospheric data produced in the DAMIP spin-up experiments  
241 themselves, covering the same period.

242

## 243 **3. Results**

244

### 245 **3.1 Observed versus simulated glacier changes**

246 By construction, there is a good consistency between the SMB estimated from stakes  
247 observations and those simulated with the SAFRAN data over the reference period 1975-  
248 2014, both in terms of mean and trends (Figure S2). The interannual variability of the SMB is  
249 slightly overestimated in the adjusted model (Figures S2). The ensemble mean of the  
250 experiment is close to the observed SMB. The cumulative SMB shows stabilised values during  
251 the 1970's followed by a dramatic retreat from the middle of the 1980's that reached a  
252 cumulated change of  $-35\text{m.w.eq.}$  (Fig. 1c) and a length change of  $-1700\text{m}$  in 2014 (Fig. 1d) as  
253 compared to the 1850 levels. The consistency between the model and the observations before  
254 1975 demonstrates that the glaciological model is able to accurately simulate both the SMB  
255 and the glacier flow (Figure 1c,1d). This also confirms the realism of the adjusted AOGCMs  
256 outputs applied to the glaciological model. The large spread in the ensemble members  
257 suggests that internal climate variability can induce large low-frequency variations of the  
258 glacier mass and length (Figure 1c,1d). This might reflect the large centennial variability  
259 simulated in this model (Jiang et al. 2021).

260

### 261 **3.2 Pre-industrial conditions**

262 The experiments are spinuped from an initial steady state imposed by the 1820 moraine, that  
263 can be simulated with a temperature decrease  $\Delta T_0 = -1.30^\circ\text{C}$  (Section 2.4.2). This  $\Delta T_0$  is close  
264 to, albeit slightly cooler, the  $\Delta T$  estimated from the AOGCM outputs that reached  $-1.15^\circ\text{C}$  in  
265 the 10-member historical experiment and  $-1.17^\circ\text{C}$  in the corresponding adjusted values  
266 (CDQM, Figure 1a). This slight difference explains that even with constant forcing levels during  
267 1820-1850 (Figure 2ab), there is a negative trend of SMB for all the members during this spin  
268 up period (Figure 2c). This negative trend is visible in the different positions of the glacier front



269 in Figure 3a, where all the members show a retreat, with a spread centred on the 1850  
270 position. This spread highlights the different positions that could have reached the glacier front  
271 with stable external forcings during this 30-year period.

272

### 273 **3.3 Forced versus climate internally driven signals**

274 For a strict comparison with the 6-member DAMIP IPSL experiments ghg, aer and nat, only  
275 the 6 corresponding members are retained in hist, as shown in Figures 2 and 3. Figure 2a  
276 highlights the local warming simulated at the Argentière Glacier in hist, starting in 1850,  
277 intensifying in the 1980's and reaching +1.42°C in 2014. This warming is mainly related to  
278 GHGs as evidenced in ghg (+1.56°C) and is partly compensated by the cooling effect of  
279 anthropogenic aerosols, as evidenced in aer (-0.74°C). The warming found in hist does not  
280 reach exactly aer+ghg+nat. Precipitation rates are stable and similar in all the experiments,  
281 suggesting a minor impact of external forcings on this variable, except in ghg for which  
282 precipitation is slightly strengthened and in aer for which precipitation is slightly decreased.  
283 Although the temperature increase due to GHGs is twice larger than the decrease due to  
284 aerosols, the GHGs and aerosols effects on precipitation nearly cancel each other. These  
285 precipitation changes are related to the radiative changes driven by greenhouse gases and  
286 aerosols, as well as potential atmospheric circulation changes (Myrhe et al. 2017). The  
287 resulting precipitation rates remain nearly unchanged in both hist and nat.

288

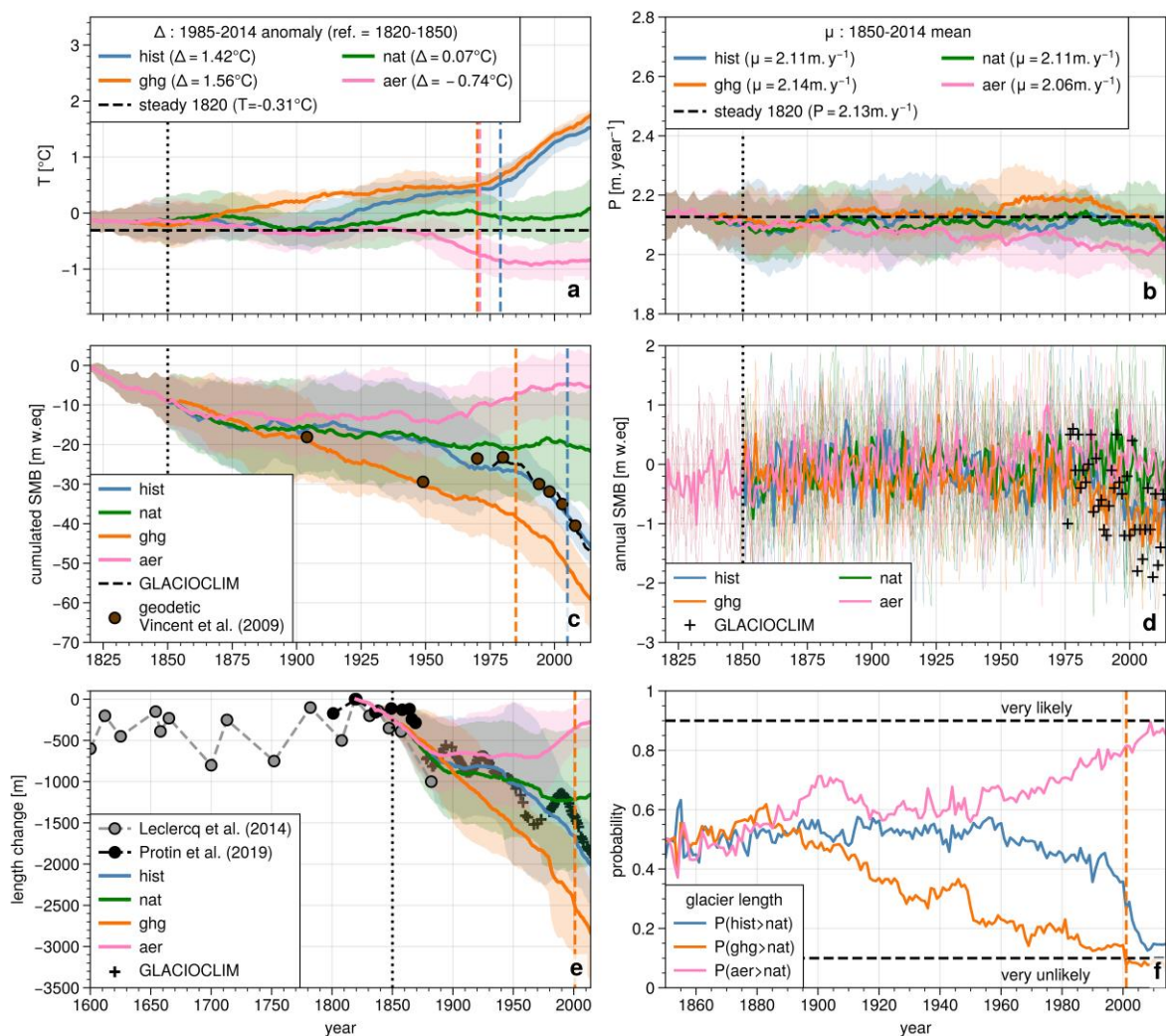
289 The cumulated SMBs show larger member spread as compared to those of temperature in all  
290 the experiments, highlighting a large imprint of climate internal variability on SMB (Figure 2c).  
291 As for temperature, the cumulated SMB simulated in 2014 under hist (~ -45m.weq) is  
292 explained by the combined but no-additive trends found in aer (~ -5m.weq), nat (~ -22m.weq)  
293 and in ghg (~ -60m.weq). SMB is decreasing in all the experiments, even in nat (~ -22m.weq).  
294 This suggests that the glacier retreat that would have occurred even without any  
295 anthropogenic forcing is related to the end of the LIA. The interannual variability of SMB is  
296 relatively high in both the observations and the model (Figure 2d), and positive values never  
297 occurred in the observations after the 2000's. The spread of the ensemble experiment is larger  
298 for the glacier length than for the SMB (Figure 2), probably explained by non-linear dynamical  
299 processes. According to geomorphologic observations (Leclercq et al., 2014), the position of  
300 the Argentière Glacier front varied between -800m and 0m over 1600-1820, reaching its  
301 maximum in 1820 (Figure 2e). In 2014, it reached -2000m in the observations, a pattern  
302 reproduced in the hist configuration that corresponds to an equilibrium between the ghg (-  
303 2800m), the nat (-1000m) and the aer (-300m) configurations.

304

305 The time of emergence is defined here as the time at which the signal of climate change  
306 emerges from the noise of natural climate variability (Hawkins and Sutton, 2012; IPCC, 2021).  
307 Here, it is estimated by computing annually the probability that the glacier is bigger than those  
308 simulated in the nat experiment after a 1000-time bootstrap resampling over the members.  
309 The vertical bars in Figure 2abcef highlight the date when this probability is very unlikely  
310 ( $P < 0.1$ ). In the ghg experiment, the time of emergence occurs in 2001 for the glacier length,  
311 in 1987 for SMB and in 1970 for temperature (orange vertical bars in Figure 2ace). The  
312 anthropogenic signal has not emerged significantly before 2014 in the hist configuration  
313 ( $P = 0.13$ ), whereas it emerged in 2008 for SMB and in 1979 for temperature (blue vertical bars  
314 in Figure 2ace).

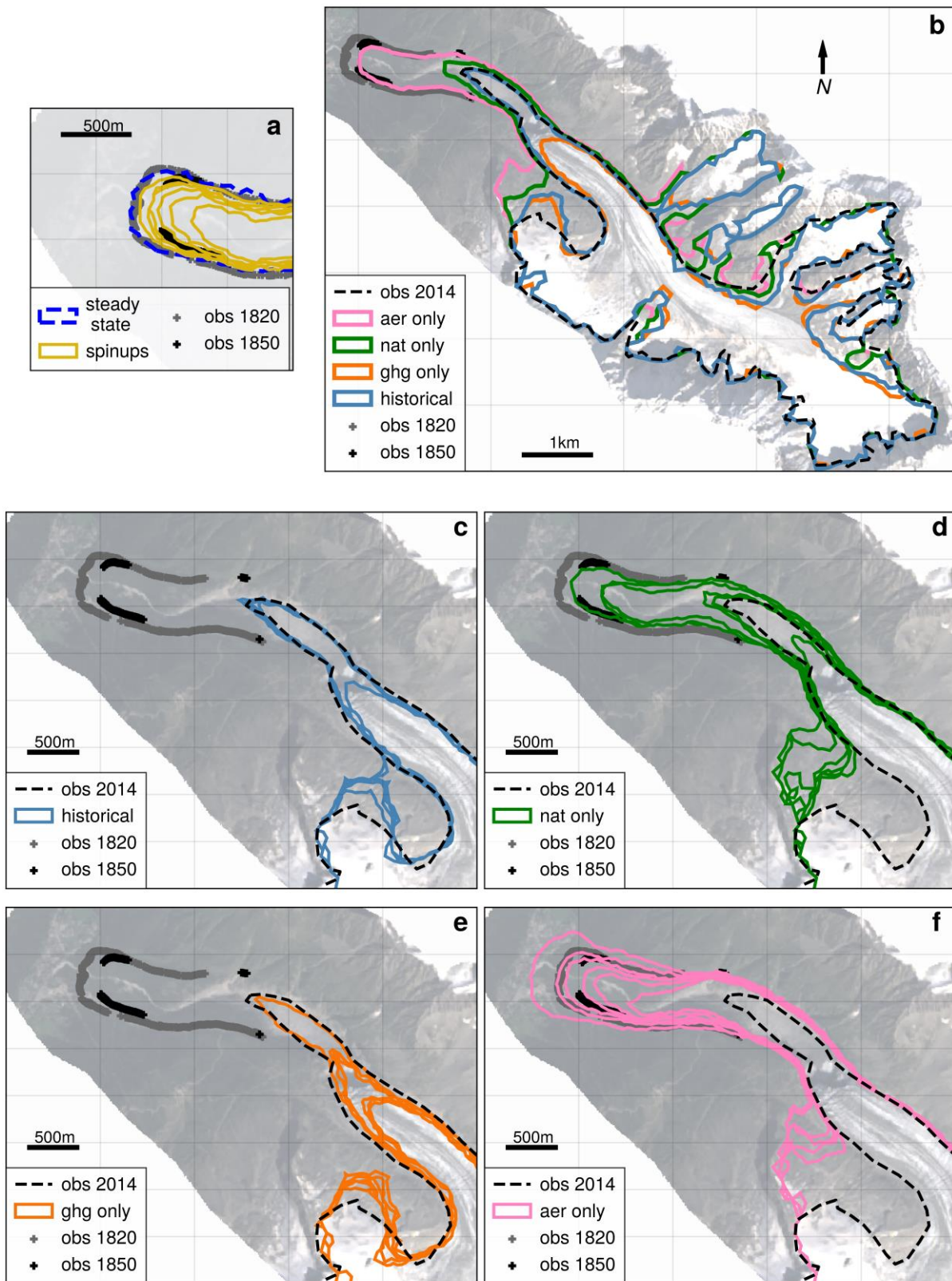
315

316 The ensemble mean of glacier extents is shown in Figure 3b: the hist configuration leads to  
 317 an extent close to the 2014 observation; the nat configuration suggests a glacier retreat less  
 318 pronounced than in the hist one; the aer configuration induces a growing of the glacier that  
 319 comes back to the levels observed during the middle of the 19th century, and the ghg  
 320 configuration leads to a retreat more pronounced than the hist one. The spatial impact of  
 321 climate internal variability on the extent of the Argentière Glacier is depicted for the four  
 322 sensitivity experiments in Figure 3abcd. Most of the hist members are concentrated close to  
 323 the 2014 observation except one that retreated more. The nat ensemble shows a large spread,  
 324 with members extending from the 1850 moraine to areas located at higher elevation than the  
 325 2014 observation. The entire ghg ensemble show extensions located at higher elevation than  
 326 the 2014 observation, whereas all the members of the aer ensemble extend until the bottom  
 327 of the valley, around the LIA moraines.  
 328  
 329  
 330



**Figure 2.** 30-year running mean of (a) adjusted temperature and (b) adjusted precipitation ; (c) cumulated SMB from 1820 ; (d) annual SMB ; (e) length change from 1820 and (f) empirical probability of having a larger glacier length than *nat* computed by comparing experiment distributions based on 1000-time bootstrap resampling. Solid lines are 6-

member means, shading corresponds to the 1- $\sigma$  member range, vertical black lines show the spin up end. Vertical coloured dashed lines indicate the year by which it is very likely or very unlikely to have a higher temperature or a lower value for SMB and glacier length than in *nat* as computed in (f). Steady 1820 in (a) and (b) refers to the mean climate conditions used for constructing the 1820 steady state.



**Figure 3.** (a) Glacier extent observed in 1820 and 1850 and simulated under pre-industrial climate conditions after a 30-year spinup experiment. (b) 6-member mean of the whole glacier area for the different experiments in 2014 and their corresponding individual members in the front area in (c) *hist*, (d) *nat*, (e) *ghg* and (f) *aer*. The black dashed line is

the observed glacier extent in 2014.

332

#### 333 **4. Discussion and conclusions**

334

335 The time of emergence of anthropogenic signals in the Argentière Glacier has been  
336 investigated using the adjusted IPSL-CM6 AOGCM to force an ice-flow model coupled with a  
337 SMB scheme. The effects of GHGs, anthropogenic aerosols and natural forcings are  
338 disentangled using dedicated detection-attribution AOGCM runs. The unavoidable adjustment  
339 required to bias-correct and downscale the AOGCM outputs to the local scale needs to be  
340 considered with caution. Here, we use a method that preserves the temperature trends from  
341 the climate model as well as the physical consistency between temperature and precipitation.  
342 Other simple statistical adjustment might result in spurious trends and erroneous accumulation  
343 rates.

344 The temperature change simulated with the AOGCM over 1850-2014 (-1.19°C) is similar to  
345 those found in HISTALP (-1.17°C) and the glacier length simulated in 1820-1850 is consistent  
346 with the morain observations. This gives credence in our modelling strategy, demonstrating  
347 that: (i) the 1850 glacier extension was an extreme state in the pre-industrial climate  
348 conditions, reached at the end of the LIA and (ii) a part of the retreat of the Argentière Glacier  
349 would have likely occurred even without any anthropogenic forcing. When excluding  
350 anthropogenic forcing, the more likely extension would have been located at an intermediate  
351 elevation between the 1850 and 2014 positions (Figure 3d). However, both the 1850 extension  
352 and positions higher than those observed in 2014 are compatible with natural variability over  
353 this period. This result is dependent on the strong multidecadal internal variability simulated in  
354 the IPSL-CM6-LR (Parsons et al., 2020). Ensemble spreads are larger in nat than in hist and  
355 ghg, suggesting that GHGs anthropogenic forcings reduced the interannual to interdecadal  
356 variability of temperature, SMB and glacier lengths over the last decades in the Alps, a  
357 hypothesis demonstrated at the global scale for the IPSL-CM6-LR model in Bonnet et al.  
358 (2021).

359 By comparing the hist and the nat experiments, the cumulative mass loss of the Argentière  
360 glacier due to anthropogenic forcing over 1850-2014 is estimated to 66% [20-112%]. This  
361 local estimation is lower than the global estimate of Roe et al. (2021), ranging between 85%  
362 and 180%, and higher than those reported by Marzeion et al. (2014), reaching 25%. Using a  
363 physical approach highly constrained by observations, we assume that the uncertainty  
364 provided here is mainly the result of climate internal variability whereas global estimates do  
365 not disentangle internal variability from model uncertainties. The similar evolution of the  
366 Argentière glacier as compared to the other Alpine glaciers over the previous centuries (Figure  
367 1c) suggests that its response to anthropogenic forcings provide a general view of the glacier  
368 changes in the Alps.

369 Overall, the length of glaciers is an interesting proxy of the decadal to centennial climate  
370 variability, because it is easy to observe and acts as climate integrators, smoothing the  
371 variability of the atmosphere at higher frequencies. Conversely, glacier lengths show a larger  
372 spread of response to climate internal variability as compared to temperature and SMB.  
373 Indeed, the front position is largely influenced by the local topographic conditions such as  
374 valley shape and slope distribution. Applying such a physical model chain allows to accurately  
375 simulate the glacier length dependency to complex terrain. The next step in the ice-flow model  
376 development concerns the basal sliding related to subglacial hydrological processes that could  
377 further enhance the spread of member experiments for glacier length.

378 The warming simulated in hist in the Mont-Blanc area does not reach the sum of the aer, ghg  
379 and nat temperature signals. The land use or stratospheric ozone that are not considered  
380 separately here could drive changes of local temperature, but these ones are expected to be  
381 small (Eyring et al. 2021). We suggest that this non-additivity results from nonlinear processes  
382 related to local feedbacks, atmospheric circulation changes and residual internal climate  
383 variability. In addition, further research using a multi-model DAMIP approach would allow a  
384 better estimation of uncertainty, since climate signals, regional circulation changes and  
385 internal variability can vary widely from one AOGCM to another one (Myrhe et al. 2017).  
386 Finally, these experiments should be repeated in further study taking into account both the  
387 cooling effect of atmospheric aerosols and the melt increase related to the deposition of  
388 absorbing aerosols, a process known for its strong impact on the cryosphere (Reveillet et al.,  
389 in press) that has been neglected here. This would allow to quantify exactly the contributions  
390 of all the external forcings that affected the cryosphere from the beginning of the industrial era.

391

## 392 **5. Acknowledgment**

393 The CMIP6 project at IPSL used the HPC resources of TGCC under the allocations 2016-  
394 A0030107732, 2017-R0040110492 and 2018-R0040110492 (project gencmip6) provided by  
395 GENCI (Grand Équipement National de Calcul Intensif). This study benefited from the ESPRI  
396 (Ensemble de Services Pour la Recherche à l'IPSL) computing and data center  
397 (<https://mesocentre.ipsl.fr>) which is supported by CNRS, Sorbonne Université, École  
398 Polytechnique and CNES and through national and international grants. All the glaciological  
399 simulations presented in this paper were performed using the GRICAD infrastructure  
400 (<https://gricad.univ-grenoble-alpes.fr>), which is supported by Grenoble research communities.  
401 This work is supported by the French ANR project SAUSSURE (ANR-18-CE01-0015-01).

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## 404 **6. Open research**

405 Observational data from GLACIOCLIM observatory are available at the following link :  
406 <https://glacioclim.osug.fr/>.

407 CMIP6 and DAMIP data is available on the Earth System Grid Federation (ESGF,  
408 <https://esgf.llnl.gov/>).

409 The modelling code is based on the open-source code Elmer/Ice available at  
410 <http://elmerice.elmerfem.org/wiki/doku.php>

411 The glacier meshing file, the glaciological model configurations, the datasets generated and  
412 analyzed and the python jupyter notebook used in the current study are available on the  
413 repository platform Zenodo at the following link : <https://zenodo.org/deposit/6786833> (to be  
414 published soon)

415

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