**Interactive comment on "Numerical modeling of the dynamics of Mer de Glace glacier, French Alps: comparison with past observations and forecasting of near future evolution" by Vincent Peyaud et al.**

## Answer to the Anonymous Referee #1

Dear Referee #1

We would like to first thanks you for your positive and constructive comments on our work.

## Main comments:

• Section 3 on the ice flow modelling contains a lot of content, which is standard in the Elmer Ice workflow and widely used. I don't see the point of recalling this again (in particular the set of equations) in the body of the paper. I suggest to replace it by appropriate references, or to move it in appendix or supplementary material to keep the paper concise and focused. Only what is specific to the Mer de Glace case should be kept in the paper's body (e.g. the choice of A relative temperate ice, the implementation of given fluxes on the domain borders, ...)
Details about the 3D mesh should also be moved to appendix. Last, modelling details normally belong to 'Methods', so I suggest to move a very concise version of Section 3 (Ice flow) to Section 4 (Methods), and possibly give further details in appendix.
Concerning the ice flow description (section 3), we agree that a long description is not necessary here. We merged the two sections "ice flow model" and "methods" in a single section 3 "Methods". To ease readability, the first subsection that described the ice flow model was shortened with only the free surface equation kept. A reference to Gagliardini et al. 2013 indicates where the reader can find more information. The "mesh" subsection was removed from the main text and displaced to the supplementary materials.

• While you mention similar existing Full Stokes-based models, or global glacier models of the Alps in introduction, you make no link at all in the discussion. Typically, questions like "How do your results compared with some recent global modelling by Zekollari and al. or other FS model of individual large-scale glacier such as Aletsch?" or "Is the Mer de Glace expected to resist better than other neighbouring glaciers?" could be addressed in your paper. Comparisons with recent other models, and other glaciers of the Alps would put your results in a broader context. In abstract and conclusion, you write "To our knowledge a comparison to data at this detail is unprecedented": This statement is vague and unsupported in the paper.
A comparison with results from other models was added at the end of the discussion.

• I feel the reading of the paper can be made more efficient if the English was improved by a professional. Line 10-12 p6 is an example of phrasing with repetitions that can be improved.
The article was already corrected by a native English speaker but we were vigilant to improve the style of the text in order to ease the reading. Your suggestions were very much appreciated.
In particular we have (i) reduced the repetitions in the text and (ii) verified the necessity of the citations and reduced their numbers.

## Specific comments

• I do not fully understand your choice of mass balance approach for the forecast simulation. A logical choice would be to simply compute the PDD everywhere instead of doing so at the Tacul gate only, and extrapolating the MB via Eq. (7). PDD can computed everywhere assuming vertical lapse rate for temperature. By doing so, you would release your hypothesis of linearly changing mass balance with respect to z. Don't you lose any information by this assumption? You could possibly tune PDDs to fit observation at Tacul in the past.

We first want to say that above the Tacul gate, when we integrate the SMB over the accumulation area, we use the vertical temperature gradient given by the climatic scenarios (meteorological variables are given every 300m). Below the Tacul gate we choose another approach, as explained in the Methods section: we calculated the SMB at Tacul gate and used the same vertical gradient as for the hindcast, mainly for consistency. This vertical gradient is derived from in-situ observations (ablation stakes, see Fig. S1).

To check the validity of this gradient, we calculated the SMB gradient for all the SMB scenarios (SAFRAN and all GCM-RCM couples). The Fig. R1-1 present the vertical gradient for SAFRAN reanalysis and the run CLM_HadCEM_RCP45, which is representative of most of our simulations. The altitude of interest (1650 to 2250 m a.s.l.), in bold, shows an interannual variability of the gradient that we didn't take into account.
We didn't test the sensitivity to the interannual variability but we calculated for each year the difference of SMB between the Tacul and the front for SAFRAN. The difference of SMB is 9.7 m a$^{-1}$ ± 0.9 m a$^{-1}$. The standard deviation is low and we assume an averaged value would lead to similar results.

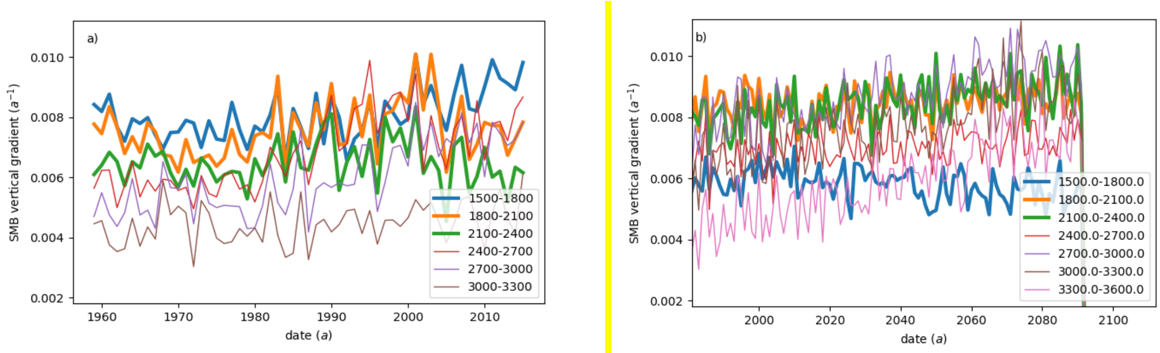


**Fig. R1-1**: *Vertical SMB gradient extracted from a) SAFRAN and b) a climatic scenario with our PDD method every 300 m. Meteorological variable are available every 300 m of altitude from 1500 to 3600 m a.s.l.: the gradients are calculated between each level and levels corresponding to the altitude of Mer deGlace are in thick lines. The example is given here for CLM_HadCEM_RCP45.*

Nevertheless, we explored the sensitivity to the gradient of SMB. For SAFRAN the averaged gradient is 0.007 a$^{-1}$ (i.e. 7 m a$^{-1}$ per km), lesser than the adopted value of 0.009 a$^{-1}$. For the climatic simulations, the value above 1800 m a.s.l. are similar the adopted value of 0.009 a$^{-1}$, below 1800 m a.s.l. the gradient is lower. We calculated the gradient between the Tacul gate and the front: from 2015 to 2050 the averaged gradient is 0.007 a$^{-1}$. The choice of these different gradients (between 0.007 a$^{-1}$ and 0.009 a$^{-1}$) leads to a maximal difference of SMB at the front of 1 m a$^{-1}$ where SMB is up to -12 m a$^{-1}$.

We performed three set of simulations, with the gradient shown in the article (db/dz=0.009 a$^{-1}$), with a lower gradient for the forecast (db/dz= 0.007 a$^{-1}$ after 2015) and with this lower gradient (db/dz= 0.007 a$^{-1}$) all along the simulations. In Fig. R1-2 we show the evolution of the velocity, thickness and front evolution for the three gradient scenarios. The differences are low, except for the evolution of the front where the SMB are the highest, especially when SMB are different since 1979.
Compared to the chosen scenario, with the lower SMB, Montenvers and Echelets gate are ice free 5 years later, in 2050 the tongue is 250 to 500 m longer.

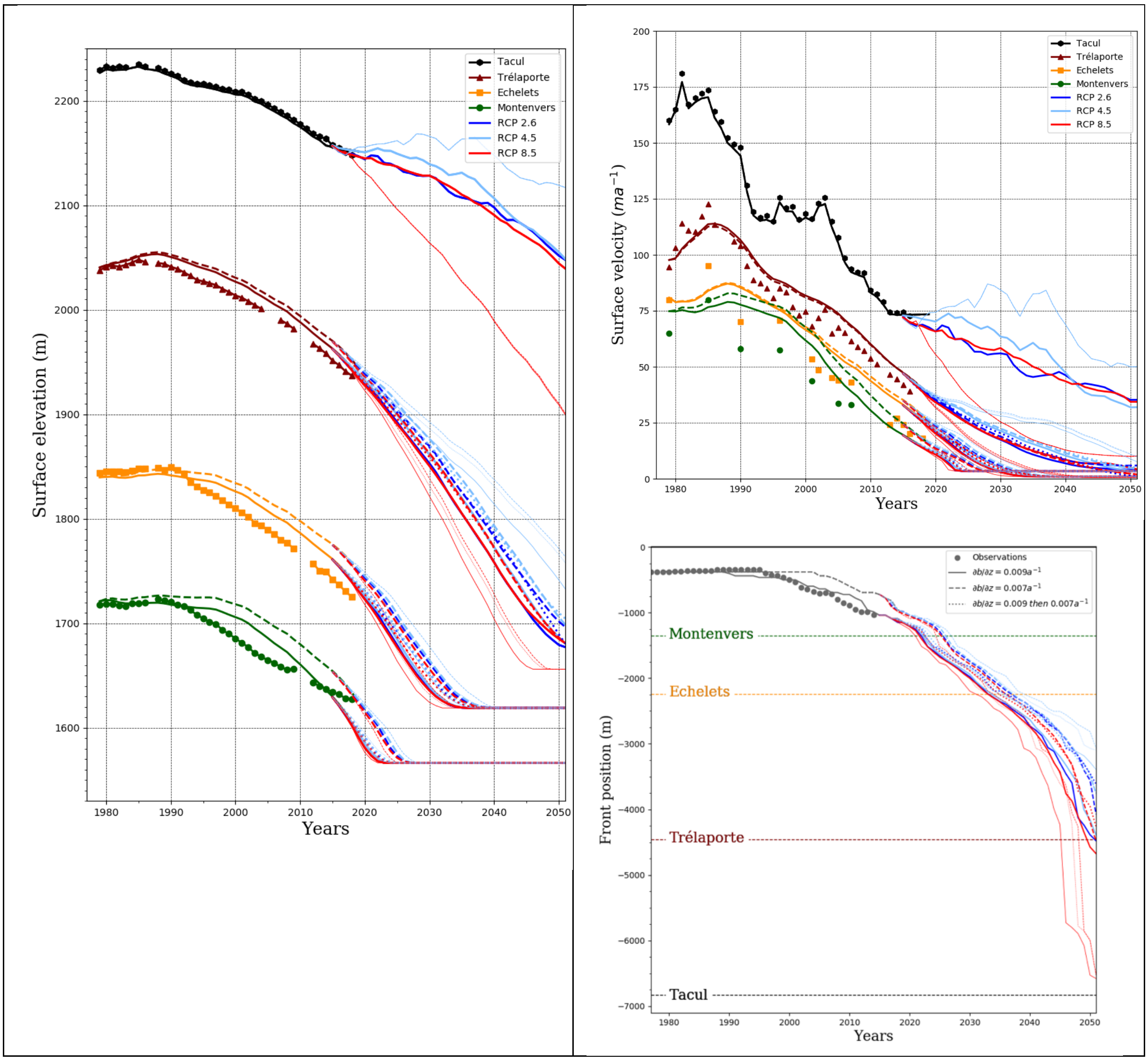


**Fig. R1-2**: *Altitude, surface velocity and front evolution for three scenarios with different SMB vertical gradient of 0.009 $a^{-1}$ (solid lines); 0.009 for hindcast and 0.007 $a^{-1}$ for forecast (dotted lines); 0.007 $a^{-1}$ (dashed line). Average RCPs scenarios are plotted with thick curves and the extremes scenarios with thin curves.*

Eq (7) Something must be wrong with this equation. Also, you have not defined zs and zs = zsTAC.
Eq (7) was effectively wrongly written. We forgot a sign '+', it is $\mathbf{b(t) = b_{tac}(t) + k_b*(zs - zs_{tac}(t))}$.
For information, this equation is numbered Eq (3) in the new version of the manuscript.
The free surface elevation zs was already defined after the free surface equation, $zs_{tac}$ is now defined in the sentence that follow Eq (7).

• l27-30 p8 'relationship between ice flux at the gate and surface mass balance upstream of the gate': Could you elaborate your method (and possible its limitations) based on the two following questions: i) can your result of 11 years be interpreted as the average time for the ice to travel from the surface to the gate? ii) This '11 year' result is probably highly dependent of the glacier regime (advancing, retreating, highly retreating ...), which is fine if you modelled the retreat over the next 3 decades, but if this is the case, can you elaborate? and thus equivalently justify your sentence l30: "It is furthermore assumed that this relationship will remain valid in the future."
The location of the Tacul gate is less than 1 kilometer downstream the ice fall where ice flows from the accumulation basin in less than a year (at speed up to 700 m $a^{-1}$). Then ice velocities are decreasing but remain high. Consequently, our result of 11 years can be interpreted as the average time for the ice to travel from the glacier du Géant to the Tacul gate. This makes us confident that this relationship flux between the flux at Tacul and integrated SMB at higher elevation will remain valid in the future.

• l16 p12 'the modeled glacier is too thick and velocity too high': this surprise me, I would expect that it is too thick because too slow following simple mass conservation principle. How do you explain that ice can be both too thick and too rapid?
Fig 5. shows that even the hindcast thin few years too late after the early growth (before 1986).
It starts to thin in 1989 at Trelaporte and around 1995 at Echelets and Montenvers gates. Then the glacier slows down and the rate of observed velocity decrease is well reproduced. However, both thicknesses and velocities are overestimated between 1990 and 2010. The trends are correct but the simulated glacier is not as reactive to the changing regime (from thickening to thinning) as expected. This explains our conclusion arguing that some transient processes, probably at the base, are missing.

• I missed where you describe the 'sensitivity experiments' of Fig. 9 and 10 in your text? I understand that the goal is test the influence of the artificial flux condition at Tacul, which is important as you only model part of the glacier by lack of data. However, this should be explained in the body of the paper, and not being left alone in Fig. 9 and 10.
At the end of the 'Methods' section we added a subsection 'Sensitivity experiments' (now 4.3, see p12) that present these additional simulations.

## Technical comments

Abstract I suggest to start straight the abstract with the 'Mer de Glace' and remove general statements (i.e. the 3 first sentences) to make the abstract more focused.
We considered with attention your suggestion. Finally, we decided to keep the 3 first sentences. We made small changes changes that considered all the comments made by the three reviewers.

l 6-7 p1 'Mer de Glace (Mont Blanc area)' => 'Mer de Glace glacier, France'. Done. Now, in the rest of the text we refer to the glacier as "Mer de Glace".

Abstract As said earlier, 'To our knowledge a comparison to data at this detail is unprecedented.'
is (too?) vague statement and not supported.
As answered earlier, we add a paragraph in the discussion to support this statement. What we considered as 'unprecedented' in this study is a comparison of geometry and dynamics with yearly in situ observations.

Abstract It is hard to evaluate how much represent 2 to 5 km without having any prior idea of the glacier size, could you instead use (or add) a relative metric? i.e. 30% to 65% of the glacier length.
We added the total length of the glacier. We didn't give relative length retreat as it depends whether we use the total length (20 km) or the modeled one (7 km).

l 21 p1 Suggest changing 'fluctuations' into 'evolutions'. Done.

l 4 p2 'Process-based model were also developed to take into account simple dynamics (...)' gives the feeling that first physically-based ice flow models started in 2015, which is obviously not the case. Could you reference early SIA-based models applied to mountain glaciers to fix this?
A reference to Le Meur et al. 2003 was added.

l 8-14 p2 You should clearly write here that by 3D physical model, you mean Stokes without any shallow-like approximations that would reduce the dimension of the equations (unless I'm mistaken?).
We added a mention to "Stokes ice flow" solution to clarify the sentence.

l 10-14 p2 Can you reduce the number of citations? Do you need all of them? It is anyway not exhaustive.
We reduced the number of citations. To illustrate the "model describing the Stokes ice flow solution for the complex three-dimensional geometry of a whole glacier has become much more affordable" we kept Jouvet and Funk 2014, Réveillet et al. 2015, Gilbert et al. 2018, and for 'Elmer/Ice has already been used for a number of glacier applications' we kept Gagliardini et al. 2011, Réveillet et al. 2015, Gilbert et al. 2018.

19-21 p2 'In addition, running simulations ... over three decades.' This is crucial here to justify the use of 3D Full Stokes to capture the complexity of the Mer de Glace ice flow, however, this is not exactly what this sentence is doing. I suggest to reformulate it to emphasize that using such a state-of-the-art model is not just an additional opportunity, but necessary to model the complex ice flow. Otherwise the reader might wonder why a simple model cannot do the job.

We reformulated the sentence to justify the use of 3D Full Stokes:

*"In addition, running simulations on this glacier provides the opportunity to fulfill the need to capture with a Full Stokes ice flow model the local complexity of ice dynamics of a glacier that presents a large expansion before the 1980 followed by a rapid retreat over three decades."*

l 21 p2 'This dynamics make it necessary to take into consideration the delay in the glacier response to climatic forcing.' This justifies to take into account the ice dynamics, but not to use a sophisticated model. Just make sure the argument is used for the right reason.
Yes, this justifies to take into account the ice dynamics. Actually, we show in this paper that, even with a sophisticated model, discrepancies remain and we conclude that "the small differences between the model and the observations arise from assuming a constant basal friction parameter". It even lets some space to further inquiry the processes involved and we think the sentence is then justified.

l 31-32 As shown in Fig. 1, Mer de Glace glacier has a single tributary glacier, which is named Leschaux glacier.
Text modified.

l5 p3 'maintained' => 'that are monitored' Done.

l6 p3 I expected to have the elevations given. monitored' Done.

l8 p3 ... they were not ... Text modified.

l11 p3 'paucity' =>) 'lack' Done

l13 p3 .. the model domain was restricted Text modified.

l14-15 p3 A transition causality word to connect the two last sentences is missing.
we added a transition causality word

l19-20 p3 Again can you reduce the number of citations?
We reduced the number of citations and kept Farinotti et al. 2017, Gilbert et al. 2020.

l29 p3 Rheological parameter with a constant value assuming temperate ice (A = 5.0159 e□24), do you mean 10□24 ? Could you give a reference for this value? Possibly consider change the unit into 158 MPa□3 a□1. This is twice the value of Cuffey and Paterson (2010).
Concerning the rheological parameter, A, a reference was added (Paterson 1994) and we modified the unit to $MPa^{-3}\ a^{-1}$.

l 8-9 p6 The two next sections describe in detail the respective boundary conditions for the two steps (hindcast and forecast) defined at the surface (mass balance) and at the Tacul and Leschaux gates (ice flux from the accumulation areas), respectively.
The original sentence was replaced by your proposition.

l10-12 p6 4 times 'surface mass balance' in 3 lines, can you improve the text? (or use an acronym)
We modified the text, rewriting a sentence and removing the unnecessary 'surface mass balance' repetitions.

l 8 p7 Define RCP and shortly comment of the meaning of the 3 pathways.
We added the term "Representative Concentration Pathway" and defined it in a new sentence.

*The 26 climate projections used here span the 3 Representative Concentration Pathway (RCP) (see Table 1 in Supplementary Material). Each RCP refers to a radiative forcings scenario considered by the IPCC and depending on the future volume of greenhouse gases emitted. They are labeled after the radiative forcing values by the year 2100 (RCP2.6, RCP4.5 and RCP8.5 corresponding to 2.6, 4.5 and 8.5 W $m^2$ respectively).*

l10 p7 'good performance', this statement calls for ad hoc references.
The 'good performance'of the degree day model is justified by a reference to Réveillet et al. 2017 who compared several SMB models with data including data from Mer de Glace.

l17 p7 ’is underestimated by climate models’: Do you mean in general or for the climate model you specifically use?
We replaced ‘by climate models’ with ‘some reanalysis datasets’ as it concerns the dataset we use. The sentence describing this dataset was rewritten to be more specific.

l21-22 p 7 For each scenario, the correction factor for precipitation is evaluated over the past period 1979-2015.
‘historical’ = ‘past’

l 38 p10 ’Fig.4.’ => ’Fig. 4.’
The missing space was added.

l6 p8 ’using the diagnostic formulation for SIA’ => ’using the SIA’. Why qualifying the SIA formula as diagnostic?
Text modified.

9) and (10) Implementing Eq (10) straight without any correction sounds hazardous as the chance to get unrealistic velocities is high as the SIA model is local (sensitivity w.r.t rs) and not tuned. In contrast, adding a correction factor that multiply Eq. (10) and is tuned to ensure continuity in time between Eq. (9) and (10) would make sense.

Eq. (9) and (10) are now numbered Eq. (5) and (6). We did not implement any corrections in Eq. (10). The vertical distribution (as the horizontal one) do not change when moving from Eq. (9) to (10). The Tacul surface elevation and velocity is the same for the hindcast and the forecast in 2015 as the flux evolution at Tacul gate is relative to 2015 (see Fig. 2).

Eq. (10) As you know the thickness here, did you consider implementing the SIA with a "shape factor" that accounts for lateral resistance of the ice flow as function of the type of profile?
Considering that we knew the real geometry of the gate and an observed surface velocity field we decided to use these data instead of a shape factor for the hindcast. Fig. R1-3 shows our velocity distribution for 2003. For Eq. (10) we could have implemented the SIA with a "shape factor" but we, as we know the real geometry, preferred to keep the same velocity distribution for consistency for hindcast and forecast.

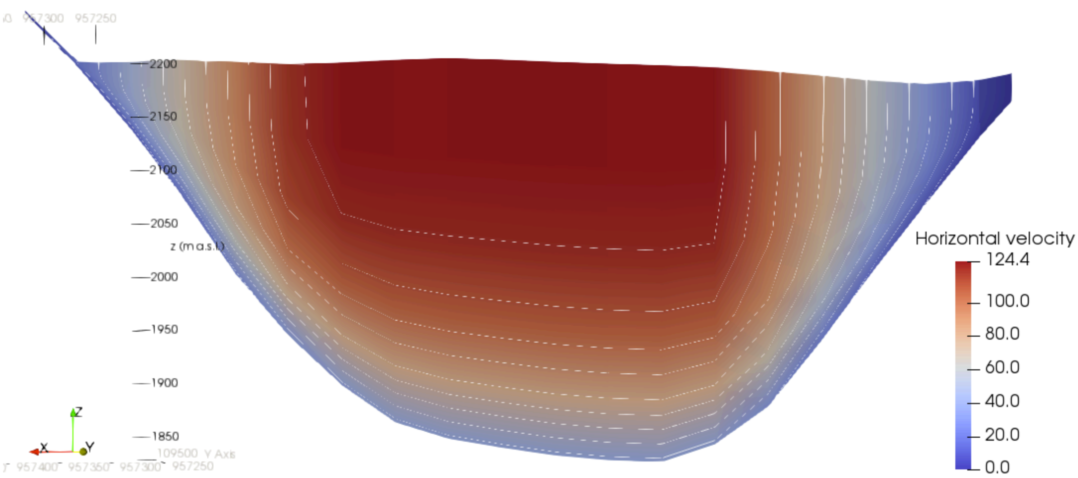


**Fig. R1-3**: *Velocity distribution at the Tacul gate of 2003.*

l14 p8 ’his maximum central value of the velocity’, do you mean ’maximum value along the transect’?
Yes indeed, the sentence was modified in:

“In all cases, ~~for the vertical evolution over the artificial boundary,~~ we assume that the form of the **vertical profile of the horizontal velocity normal to the flux gate** ~~vertical profile of the normal velocity~~ is given by the Shallow Ice Approximation…”

l15 p8 ’above transverse velocity profile’: refer to Eq. (9).
We changed the reference for the good equation (old Eq. (9)., now Eq. (6)).

l16 p8 ’Despite the differences in the methods’ I’m not sure what are the 2 methods you referring: Eq. (9) vs Eq. (10)? Please, clarify.
As this point, we were comparing our method with the method that Berthier and Vincent (2012) used to infer the flux at Tacul.

l28 p8 Repeat the reference to Durand for the Safran reanalysis. Done.

l15 p11 It can be surprising to see so tiny differences between different RCPs. You may say that this was expected as RCPs differ substantially more after 2050 (if I’m not mistaken).
Indeed, the RCPs differ after 2050, a new sentence was added:

> “*Large differences between the pathway scenarios appear only after 2050 (not shown)*”

l 30 p11 "However, these strong differences in ice thickness and ice flux at the Tacul gate lead to much smaller absolute differences in thinning and ice flow velocity downstream of the gate; the lower the cross section, the smaller the response differences for the different scenarios." If you were normalizing the model discrepancies by the ice thickness or ice velocity at the gate, the differences would probably be more uniform, isn’t it?

We plotted the normalized model/observation discrepancies by the ice thickness or ice velocity at the gate in the Fig. R1-4. The normalized thickness discrepancies are similar for the three gates. Discrepancies at Montenvers gate have a greater amplitude which may be due to the low thickness and largest sensitivity to SMB evolution. The same behavior seems to occur for the velocity discrepancies but observation at the Montenvers and Echelets are sparse.

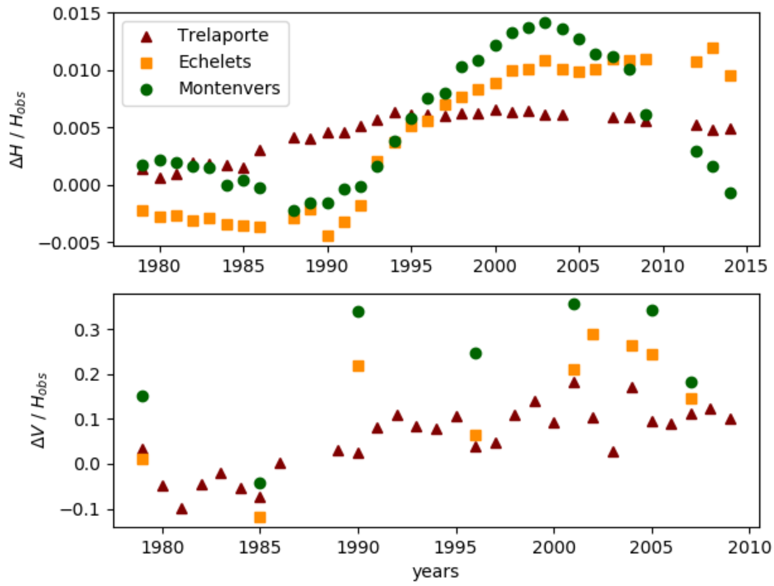


**Fig. R1-4**: *Thickness and velocity differences (model-observation ) normalized by the observations for the 3 lower gates.*

l1 p12 ’assess’ => ’estimate’ or ’forecast’ or ’predict’
’assess’ => ’estimate’

l5 p13 ’which is low relative to the mean ablation measured on the tongue of Mer de Glace’ can you give a number?
The ablation at Tacul gate is given in the Fig. 2a. The ablation measurements are provided in the supplementary materials. It corresponds to ~4 m $a^{-1}$ at Tacul and more than 10 m $a^{-1}$ at Montenvers.

l6 p13 ’Other uncertainties arise from the linear extrapolation of ablation over the tongue (Eq. (7)) based on measurements in an area of clean ice’, your assumption of linear MB w.r.t altitude might by the highest source of uncertainty? If yes, it would make sense to start with this.

We think there is two sources of uncertainties in our hindcast. One can result from the dynamics (most probably the constant sliding coefficient), and the other is attributed to our SMB model. Concerning the SMB we decided

to choose a simple approach as Réveillet et al. 2017 showed that a classical degree-day model was sufficient to simulate the long-term glacier-wide MB.
For the hindcast we had the choice to use a PDD using SAFRAN reanalysis (with meteorological variables available every 300 m of elevation) or the observations. We answered earlier the reason why we choose a linear MB w.r.t altitude.

The tongue of the Mer de Glace has an increasing debris cover, which is until now, restricted to the last kilometer downstream the Echelets gate. We assume that it partially protected the front during the two last decades. While it is difficult to know how the debris cover will evolve above Echelets gate in the future we have not taken this parameter into consideration in the siulations. However, we are conscious that it could lead us to overestimate front retreat.

l8 p13 Please reference to a Figure.
We added a reference to the (now) Fig. 5.

l10 p 13 'is also well known' => 'is also well constrained'. Corrected.

l11 p 13 not underestimated by the model... But Fig. 5 shows a slight but real systematic over-estimation of velocities, isn't?
As mentioned in the answer to Specific comments, Fig 5. shows that velocity increase during the glacier growth before 1986 is underestimated. Then the glacier slows and the rate of observed velocity decrease is well reproduced by the model at the three gates. These changes follow the thickness evolutions. Both thicknesses and velocities are overestimated between 1990 and 2010: thickness because the simulation seems to thin few years too late and velocity because the glacier is too thick.

l12 p 13 To what 'discrepancies' do you refer? In the sentence before, you say there is no major discrepancies in velocities.
The trends are correct, the model reproduce the growth and then the decay of the glacier but the simulation is not as reactive to the evolution at Tacul gate as expected by observations.

l1-4 p14 One can also argue an inaccurate sliding ratio to explain model errors? Have you considered testing different rate factors A to increase or decrease vertical deformation?
We didn't test different rate factors A. Indeed, the uncertainties on this factor may explain some model errors.

l13 p15 'will start to increase ...' => 'is expected to increase ...', check not to use future tense when you describe model results, but conditional or equivalent. Same for the sentence right after.
Tense were corrected in both sentence.

## Figures:

Concerning the figures, all your suggestions were taken into account:

Fig 2. SMB not defined. How is it possible that different RCPs show different values in the past times?
SMB was defined in the caption for the level of Fig 2a.
In the past times the mean RCPs show different values as does not comprehend the same number of model (for instance there is 3 models for RCP 2.6, 11 models for RCP 4.5 and 13 for RCP 8.5.

Fig 4. Formulation (Eq. (10)),
Fig 4. observed surface velocity, ice thickness, and a velocity distribution given
Legend of Fig. 4 was corrected.

Fig. 6 "Same as Fig. 5, but for surface elevation." Please make a full sentence. For convenience, better to repeat the text to make each individual caption self-contained. Another possibility is to merge Fig. 5 and Fig. 6, with two panels.
The same for Figs. 9 and 10.
Fig. 5 and Fig. 6, as well as Figs. 9 and 10 were merged.

Fig. 8 colorbar is missing
Fig. 8: a colorbar was included.

Fig. 10 Color coding missing. Again, the Figure would be better if self-contained without having to look for the color coding in another Figure. Otherwise merge Fig. 9 and 10 with two panels.
Figs. 9 and 10 were merged.

Vincent Peyaud, on the behalf of the coauthors.

# Numerical modeling of the dynamics of Mer de Glace glacier, French Alps: comparison with past observations and forecasting of near future evolution.

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Correction in response to the reviews are in blue.

**Abstract.**

~~All alpine glaciers are shrinking and retreating at an accelerating rate in a warming climate~~ Alpine glaciers are shrinking and rapidly lose mass in a warming climate. Glacier modeling is required to assess the future consequences of this retreat on water resources, the hydropower industry and risk management. However, the performance of such ice flow modeling is generally difficult to evaluate because of the lack of long-term glaciological observations. Here, we assess the performance of the Elmer/Ice full-Stokes ice flow model using the long dataset of mass balance, thickness change, ice flow velocity and snout fluctuation measurements obtained between 1979 and 2015 on the Mer de Glace glacier, France. Ice flow modeling results are compared in detail to comprehensive glaciological observations over four decades including both a period of glacier expansion and a long period of decay. To our knowledge a comparison to data at this detail is unprecedented. We found that the model accurately reconstructs the velocity ~~, and~~ elevation and lengh variations of this glacier despite some discrepancies that remain unexplained. The calibrated and validated model was then applied to simulate the future evolution of Mer de Glace from 2015 to 2050 using 26 different climate scenarios. Depending on the climate scenarios, this glacier, the largest in France with a length of 20 km, could retreat by 2 to 6 km over the next three decades.

## 1 Introduction

Mountain glacier mass balances show a strong sensitivity to climate change and can thus be used to assess the impact of climate change in remote areas (Oerlemans, 2001; Zemp et al., 2019). During the 20th century, all alpine glaciers showed a strong recession (Zemp and Frey, 2015). This observed trend is expected to continue in the future under a warming climate (IPCC, 2019) with important impacts on watershed hydrology (Huss and Hock, 2018; Brunner et al., 2019), tourism and hydropower resources (e.g. Welling et al., 2015; Stewart et al., 2016), accompanied by the emergence of new risks (e.g. Kääb et al., 2018) and sea-level rise (Hock et al., 2019; Marzeion et al., 2020). Properly assessing these future impacts requires the development of modeling tools capable of describing the processes driving these glacier changes.

Numerical ice flow models with different degrees of complexity have been developed to forecast glacier fluctuations evolutions. The first studies (since Haeberli and Holzle, 1995) focused on an empirical approach in which ice dynamics were not taken into account explicitly and glacier evolution was based on parameterization calibrated either on equilibrium-line altitude (ELA) model (e.g. Zemp et al., 2006), extrapolation of observed geometry changes (e.g. Huss et al., 2008; Huss, 2012; Huss and Hock, 2018) or volume and length–area scaling (e.g. Marzeion et al., 2012; Radic et al., 2014). Process-based model were also developed to take into account simple dynamics (e.g. Le Meur and Vincent, 2003; Clarke et al., 2015; Zekollari et al., 2019; Maussion et al., 2019). The first studies of an individual glaciers (e.g. Huybrechts et al., 1989; Letréguilly and Reynaud, 1989; Stroeven, 1989; Greuell, 1992) were restrained to flowline model related to the local driving stress while studies on regional scale (since Haeberli and Hölzle, 1995) focused on an empirical approach in which ice dynamics were not taken into account explicitly and glacier evolution was based on parameterization calibrated either on equilibrium-line altitude (ELA) model (e.g. Zemp et al., 2006), extrapolation of observed geometry changes (e.g. Huss et al., 2008; Huss, 2012; Huss and Hock, 2018) or volume and length–area scaling (e.g. Marzeion et al., 2012; Radić et al., 2014). Process-based model were also developed to take into account simple dynamics (e.g. Le Meur and Vincent, 2003; Clarke et al., 2015; Zekollari et al., 2019; Maussion et al., 2019). These studies suggest a glacier volume loss from 65% to 94% in the Central Europe by the end of the century depending on the climate scenario (IPCC, 2019; Marzeion et al., 2020). However, the Fourth IPCC Assessment Report (Solomon et al., 2007) and other studies (e.g. Vincent et al., 2014) emphasize the need for a new generation of glacier models that accurately describe the ice flow dynamics to correctly forecast individual glacier evolution. Today, such three-dimensional physical models are widely available. Indeed, with the increase in the performance of computational resources improvement of computational resources performance, running a model describing the Stokes ice flow solution for the complex three-dimensional geometry of a whole glacier has become much more affordable (e.g. Réveillet et al., 2015; Jouvet and Huss, 2019; Gilbert et al., 2020). Among such models, Elmer/Ice (Gagliardini et al., 2013) has already been used for a number of glacier applications (e.g. Gagliardini et al., 2011; Réveillet et al., 2015; Gilbert et al., 2020) and will be used for this study.

However, very few glacier datasets are available to make a detailed comparison between observed and modeled fluctuations at the multi-decadal scale. The Mer de Glace glacier offers a rare opportunity to compare state-of-the-art model results with a large dataset containing observed thickness changes, ice flow velocities and snout fluctuations over a nearly continuous 40-year period thanks to the GLACIOCLIM observatory monitoring program (Vincent, 2002; Vincent et al., 2014; Berthier et al., 2004, 2005, 2014; Berthier and Vincent, 2012). In addition, running simulations on this glacier provides the opportunity to fulfill the need to capture with a Full Stokes ice flow model the local complex ice dynamics of a glacier that presents a large expansion ? before the 1980s followed by a rapid retreat over three decades. These dynamics make it necessary to take into consideration the delay in the glacier response to climatic forcing.

In this paper, the performance of the Elmer/ice ice-flow model is first assessed in terms of its ability to reconstruct these past multi-decadal fluctuations of the tongue of the Mer de Glace. A thorough comparison makes it possible to explore the sources of discrepancies between the reconstruction and the observations. In a second step, prognostic simulations are performed to simulate the evolution of the ~~Mer de Glace~~ glacier until 2050 under different climate scenarios.

## 2 Study site and glaciological data

Mer de Glace ($45°55'$ N, $6°57'$ E), the largest glacier in the French Alps, covers an area of 32 $\mathrm{km}^2$. It is located in the Mont Blanc massif (Fig. 1) and is monitored as part of the GLACIOCLIM observatory (https://glacioclim.osug.fr/). The maximum elevation of its upper accumulation area reaches 4300 $\mathrm{m}$ a.s.l. From this accumulation region, the ice flows at speed up to 700 $\mathrm{ma}^{-1}$~~rapidly~~ through a narrow, steep portion (an icefall between 2700 and 2400 $\mathrm{m}$ a.s.l.) before feeding the lower, 7 $\mathrm{km}$ long section above the terminus ~~part of the glacier down to a front~~ located at 1534 $\mathrm{m}$ a.s.l. in 2018. As shown in Fig. 1, ~~Leschaux glacier is the only active tributary of Mer de Glace glacier~~ Mer de Glace has a single tributary glacier, which is named Leschaux glacier.

Several surface Digital Elevation Models (DEM) are available for different time in the past. The first map was produced by Vallot (1905) using the classical topographic method in 1905. Another DEM was made by Institut Géographique National (IGN) in 1979 and two by the Laboratory of Glaciology of Grenoble in 2003 and 2008 using aerial photographs (Vincent et al., 2014). A surface velocity field was derived from SPOT 5. Moreover, continuous field measurements have been performed in the lower part of the glacier (below 2300 $\mathrm{m}$ a.s.l.) from a network of stakes ~~maintained~~ that are monitored continuously since 1979 at four different elevations: the Tacul (2148 $\mathrm{m}$ a.s.l. in 2018) , Trélaporte (1937 $\mathrm{m}$ a.s.l.), Echelets (1725 $\mathrm{m}$ a.s.l. ) and Montenvers (1627 $\mathrm{m}$ a.s.l.) cross sections (see Fig. 1). Surface elevation has been measured systematically each year since 1979 along these four cross sections. Surface mass balance and annual surface velocity observations are also available at these cross sections although they ~~are~~ were not continuous between 1979 and 1994, except for observations at the Tacul glacier cross section which are continuous over the whole period. The bedrock topography was determined below 2300 $\mathrm{m}$ a.s.l. using mechanical borehole drillings, seismic soundings (Süustrunk, 1951; Vallon, 1961, 1967; Gluck, 1967) and radar measurements (2018, not published).

Given the ~~paucity~~ lack of bedrock topography measurements in the upper part of the glacier (above the ice fall of Géant glacier) and the absence of measurements of bedrock topography for Leschaux glacier, the model domain ~~is~~ was restricted to the lower part of the glacier from Tacul glacier down to the snout. Here, we assume that the contribution of the Géant and Leschaux glaciers to the Mer de Glace ~~glacier~~ can be represented as specified flux conditions on the boundary of the Mer de Glace model.

## 3 Methods

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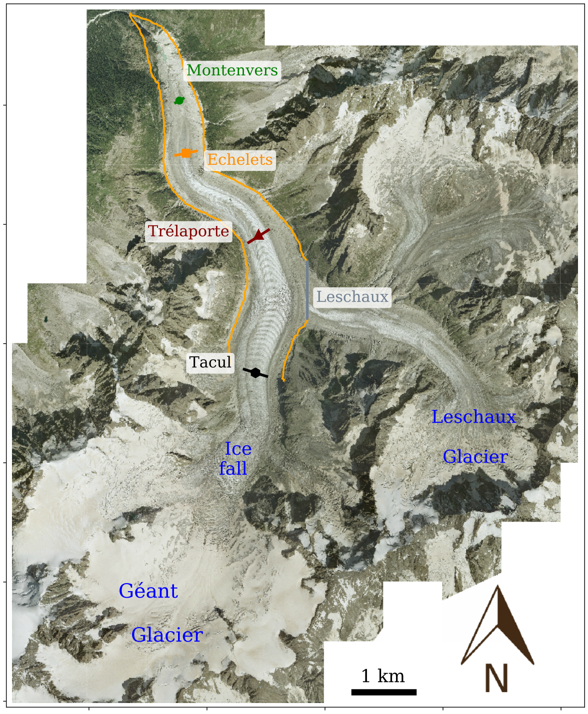


**Figure 1.** Map of Mer de Glace (orthophotoplan acquired in 2008 ©RGD74). Orange contour delimits the area modeled in this study. The location of the four cross sections (Tacul, Trélaporte, Echelets and Montenvers) and the Leschaux gate are indicated by the colored lines. The Tacul and Leschaux gates represent boundary gates where data areis used to force the model whereas , the three other profiles represent internal gates where data areis used to validate the model.

### 3.1 Ice flow model

Mer de Glace ice flow dynamics are modeled with the Elmer/Ice open-source finite-element model (Gagliardini et al., 2013). This model has been applied to simulate real and artificial mountain glaciers (e.g. Farinotti et al., 2017; Gilbert et al., 2020) The main equations solved within Elmer/Ice are summarized below. For more details regarding their numerical implementation, the reader can refer to Gagliardini et al. (2013) and the papers listed herein.

The 3d velocity field $\boldsymbol{u} = (u, v, w)$ and $p$, the isotopic pressure, are solution s of the Stokes equations that expresses conservation of momentum and conservation of mass for an incompressible fluid. We use the viscous isotropic nonlinear Glen's law (Glen, 1955) to link the deviatoric-stress tensor to the strain-rate tensor. The Glen's exponent is $n = 3$ and assuming temperate ice the rheological parameter $A$ has a constant value ($A = 158\ \mathrm{MPa}^{-3}\mathrm{a}^{-1}$, Paterson, 1994). Indeed, the ice of the lower part of the Mer de Glace glacier is most likely temperate (Lliboutry et al., 1962).

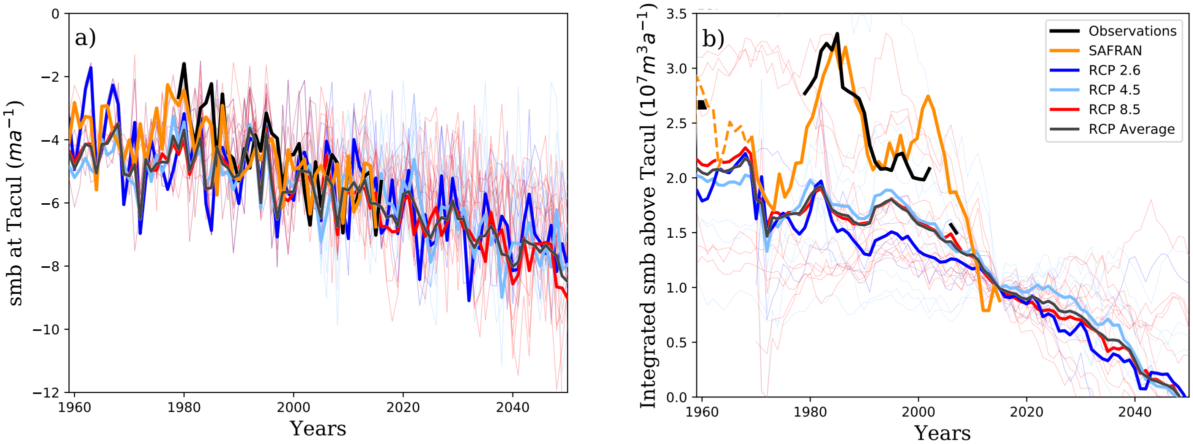


**Figure 2.** Evolution with time from 1960 to 2050 of a) the surface mass balances (SMB) at Tacul gate and b) the integrated surface mass balance above Tacul gate. Observations are presented in black and values inferred from SAFRAN in green. The others climate scenarios are plotted in dark blue (RCP 2.6), blue (RCP 4.5) and red (RCP 8.5); the average values for each scenario are highlighted by thick curves. Note that for the past period 1960-2015, the integrated surface mass balance above Tacul gate in b) does correspond to the flux at this gate and that "observations" are not from direct observations but are actually estimated from surface velocity and elevation following method used in Berthier and Vincent (2012). All integrated surface mass balances for the forecast simulations are normalized to the 2015 observed mass balance.

The upper surface of the glacier is a free surface of elevation $z_s$ (m) that evolves with time according to the kinematic equation:

$$\frac{\partial z_s}{\partial t} + u_s \frac{\partial z_s}{\partial x} + v_s \frac{\partial z_s}{\partial y} - w_s = b(z_s, t), \tag{1}$$

where the surface mass balance $b(z,t)$, in ice equivalent thickness ($\mathrm{m\,a^{-1}}$), is a function of surface elevation and time and $\boldsymbol{u_s} = (u_s, v_s, w_s)$ denotes the surface velocity vector. As the finite element mesh cannot have a null thickness, a lower limit of 1 m above the bedrock elevation is applied to $z_s$ in Eq. 1.

### 3.2 Boundary conditions

At the base, ice cannot penetrate into the bed so the velocity component normal to the bed is null. As Mer de Glace are~~glacier~~ is a temperate glacier, a certain amount of sliding on its bed is expected. A linear friction law relating the basal shear stress $\boldsymbol{\tau_b}$ to the basal velocity $\boldsymbol{u_b}$ is applied on the lower boundary:

$$\boldsymbol{\tau_b} + \beta \boldsymbol{u_b} = 0. \tag{2}$$

The time-independant basal friction parameter distribution $\beta(x,y)$ is inferred using an inverse method described in Gillet-Chaulet et al. (2012). This method relies on the computation of the adjoint of the Stokes system and the minimization of a cost function that measures the mismatch between modeled and observed velocities, using the surface topography and surface velocities measured in August 2003 (Berthier et al., 2004). The value of the basal friction parameter is kept constant in both past and future simulations. On the upper surface, the surface mass balance, required in the ~~glacier-~~free surface equation (Eq. 1), is derived either from observations when available or based on a positive degree-day (PDD) model forced by climate simulations for future. The two methods are explained in detail in Section 3.3.

As the model domain does not cover the whole glacial catchment (see Fig. 1), ice flowing from the main accumulation area through the Tacul gate and from the tributary glacier (Leschaux) add two flux boundary conditions on the side of the domain. The flux coming from the upper part of the glacier through the Tacul gate boundary condition is imposed from observations (thickness and central horizontal velocity at the Tacul gate) from the past and the estimated flux in the future. A similar method based on a flux is applied at the junction with Leschaux glacier. The implementation of an ice flux at these two gates for hindcast and forecast simulations differs slightly and is described in detail in Section 3.4.

Our simulations cover the period 1979-2050. The hindcast simulation covers the period 1979-2015 for which are~~annual~~ surface mass balances, surface velocities and elevation changes are available yearly at the four cross sections of Tacul, Trélaporte, Echelets and Montenvers (Fig. 1). The dataset at the Tacul cross section is used to specify the flux on this artificial boundary of the glacier domain, while the 3 others are used to prescribe futur fluxes through the boundary ~~evaluate the model over the hindcast period~~. For the forecast simulations from 2015 untill 2050, results from climate simulations are used to ~~evaluate the flux on the different boundary conditions of the glacier domain~~ simulate the future flux evolution at the boundary of the glacier domain. ~~This section describes in detail the respective boundary conditions for the two steps (hindcast and forecast) defined at the surface (surface mass balance) and at the Tacul and Leschaux gates (ice flux from the accumulation areas).~~
The two next sections describe in detail the respective boundary conditions for the two steps (hindcast and forecast) defined at the surface (mass balance) and at the Tacul and Leschaux gates (ice flux from the accumulation areas), respectively.

### 3.3 Surface mass balance

For the hindcast simulation, surface mass balance is derived from observations acquired during the historical period 1979-2015 (Six and Vincent, 2014, Fig. 2a). The surface mass balance at a given elevation is reconstructed according to an empirical relation with the one observed at the Tacul cross section gate for the same year, according to:

$$b(z_s,t) = b_{\text{TAC}}(t) + k_b\left[z_s(t) - z_{s\text{TAC}}(t)\right] , \tag{3}$$

where $b_{\text{TAC}}(t)$ is the annual surface mass balance measured (hindcast) or evaluated (forecast) at the Tacul altitude $z_{s\text{TAC}}$. The vertical ~~mass balance~~ gradient $k_b = \partial b/\partial z$ was estimated using the yearly ~~surface mass balance~~ measurements at the four profiles from 1995 to 2015 (see Fig. S1 in the Supplementary Material). A mean value of $k_b = 0.009\ \text{m}^{-1}$ is obtained with a standard deviation of $0.002$. Despite this strong variability from year to year (Fig. S1 in the Supplementary Material and Rabatel et al., 2005), a constant surface mass balance gradient of $k_b = 0.009\ \text{m}^{-1}$ is adopted for hindcast and forecast simulations.

For future simulations, the surface mass balance at Tacul gate in Eq. (3) is inferred from a series of 26 downscaled and adjusted regional climate projection of the EURO-CORDEX program (Jacob et al., 2014). The adjustment was performed using the ADAMONT method (Verfaillie et al., 2017) using the SAFRAN reanalysis (Durand et al., 2009) as an observation reference, as described in Verfaillie et al. (2018). The 26 climate projections used here span the 3 ~~IPCC scenarios~~ Representative Concentration Pathway (RCP) ~~RCP2.6, RCP4.5 and RCP8.5~~ (see Table 1 in Supplementary Material). Each RCP refers to a radiative forcings scenario considered by the IPCC and depending on the future volume of greenhouse gases emitted. They are labeled after the radiative forcing values by the year 2100 (RCP2.6, RCP4.5 and RCP8.5 corresponding to 2.6, 4.5 and 8.5 $Wm^2$ respectively).

A degree-day model (Braithwaite, 1995; Hock, 2003), known for its simplicity and relatively good performance (Réveillet et al., 2017), is used to evaluate the surface melt at Tacul gate from the ~~modeled~~ air temperature. Surface melting is proportional to the sum of positive degree-days (PDD, i.e. the sum of daily mean temperatures above the melting point over a given period of time) assuming different melt factors for snow and ice. These melt factors, here expressed in ice thickness equivalent, are $0.0048\ \mathrm{mK^{-1}d^{-1}}$ for snow and $0.0053\ \mathrm{mK^{-1}d^{-1}}$ for ice as calibrated by Réveillet et al. (2017) for the Mer de Glace. The surface accumulation is the sum of the solid precipitation (snow) and winter liquid precipitation (rain); it is assumed that during winter any rain that falls freezes and remains in the snow pack. Previous works (e.g. Gerbaux et al., 2005; Réveillet et al., 2017; Vionnet et al., 2019) show that precipitation is underestimated ~~by climate models~~in some reanalysis datasets. Comparison of precipitation simulated by SAFRAN reanalysis (Durand et al., 2009) with the annual surface mass balance at Tacul between 1979 and 2015 and with the observed winter accumulation data available after 1994 in the accumulation area (see Supplementary Material) indicates that the SAFRAN precipitation must be increased by 63% to best fit the observations, in good agreement with Réveillet et al. (2017). The same method is then repeated for the climate scenarios adopted for this study. For each scenario, the correction factor ~~on~~ for precipitation is evaluated over the ~~historical~~past period 1979-2015. On the average, simulated precipitation must be increased by 70% to fit observations, with only slight differences from one scenario to another. The value of 70% is therefore applied to all scenarios. The surface mass balance at Tacul gate obtained after 2015 with the PDD model and the corrected precipitation from the 26 different climate scenarios constitute the forcing data for the 26 forecast simulations. The same relation as for the hindcast simulation (Eq. (3)) is then used to infer the spatial distribution of surface mass balance.

### 3.4 Flux through the Tacul gate

To account for the artificial boundaries at Tacul and Leschaux gates, normal ice velocities over these boundaries and changes in surface elevation are imposed as Dirichlet boundary conditions for the Stokes ~~(Eqs. (??) and (??))and~~ free surface equations (Eq. (1)), respectively. The treatment is different for hindcast and forecast simulations, but also for Tacul and Leschaux, given that Leschaux has much less data.

In all cases, ~~for the vertical evolution over the artificial boundary,~~ we assume that the form of the vertical profile of the horizontal velocity normal to the flux gate~~vertical profile of the normal velocity~~ is given by the Shallow Ice Approximation (SIA, Hutter, 1981). From the results of the inversion of basal friction performed over the whole domain using the 2003 observed surface velocity, we further assume a constant and uniform ratio between sliding and surface velocities of $1/3$ at both gates ($r_{\text{slid}} = u_b/u_s = 1/3$). The vertical profile of the normal velocity at the gate is evaluated as

$$u(z) = r_{\text{slid}} u_s + u_d(z)\,, \tag{4}$$

in which the deformational velocity is either imposed knowing $u_s$ (hindcast simulations at Tacul) as

$$u_d(z) = (u_s - u_b)\left(\frac{z - z_b}{H}\right)^{n+1}, \tag{5}$$

or evaluated using the diagnostic formulation for SIA (forecast at Tacul):

$$u_d(z) = 2A\,(\rho_i g \nabla H)^n\,(z - z_b)^{n+1}\,. \tag{6}$$

In the above equations, $z_b$ is the bedrock elevation whereas $H$ denotes ice thickness. In Eq. (6), the surface slope $\nabla H$ is the 2003 value and is held constant with time.

The transverse profile of surface velocity is assumed to follow the 2003 SPOT5 surface velocity at the Tacul cross section (see Fig. 7b in Berthier and Vincent, 2012): it is null on the side and increases linearly from both sides of the glacier to reach a maximum central value uniform over a constant width of 400 $\mathrm{m}$.

For the hindcast simulation, this maximum central value ~~of the velocity~~, denoted $u_{s\text{TAC}}$, is given from observations, as is also the case for the ice thickness $h_{s\text{TAC}}$. Knowing both the surface velocity $u_s = u_{s\text{TAC}}$ and ice thickness $H = h_{s\text{TAC}}$ in Eq. (5), and assuming the above transverse velocity profile, the total flux through the gate can be estimated (see Fig. 2b). Despite the differences in the methods to estimate the ice flux at the gate~~, the inferred flux using this approach~~ our inferred flux is consistent with the previous estimation of Berthier and Vincent (2012) (see Fig. 3) who assumed constant ratios of 0.8 between the width-averaged and observed center-line surface velocities and of 0.9 between depth-averaged and width-averaged surface velocities. The assumptions on transverse and vertical velocity profiles with $r_{\text{slid}} = 1/3$ we use in our modeling leads respectively to ratios of 0.75 and 0.85, very close to the ones adopted by Berthier and Vincent (2012), explaining the closeness of the two approaches.

For the forecast simulations, $u_s$ and $H$ are unknown. Instead, the flux is directly evaluated from the integrated surface mass balance above Tacul gate (see Fig. 2b) and then used to determine the value of $H$ and the velocity distribution at the gate from Eq. (6). Ice flux through the gate is assessed by integrating, upstream of the Tacul gate, the surface mass balance given by the climate scenarios. For steady state conditions, the ice flux should be equal to the sum of the surface mass balance obtained over the whole area of the upper part. In reality, the glacier being in a highly unsteady state, this condition is not fulfilled. To estimate the relationship between ice flux at the gate and surface mass balance upstream of the gate, we use the observations made between 1979 and 2015 and the reconstructed surface mass balance using Safran reanalyses (Durand et al., 2009). It is found that the observed ice flux at the Tacul gate is best estimated by averaging the surface mass balance integrated upstream of the gate over the 11 previous years (Fig. 3). It is furthermore assumed that this relationship will remain valid in the future.

The inferred relationships between ice flux, velocity and thickness at Tacul gate are shown in Fig. 4. This figure also presents these relations for the available observations (1979-2015). Their comparison confirms the validity of the empirical relations used above. As shown by Fig. 2b, some scenarios lead to a negative integrated surface mass balance above the Tacul gate, which could result in a very small or even null flux at the gate when integrated over 11 years. To avoid physically meaningless overly large decrease of $H$ (a zero flux would imply an instantaneous decrease of $H$ to zero), the annual decrease of $H$ at the Tacul gate is bounded by the local annual surface mass balance because the modeled thickness changes cannot be more negative than ablation. Moreover, to ensure the physical consistency of this boundary condition over the whole simulation period, surface velocity and thickness cannot be null. In applying ~~application of~~ this second condition, the minimal thickness in our simulation is always greater than $70\ \mathrm{m}$. For surface velocity, a minimal condition of $10\ \mathrm{m\,a^{-1}}$ is applied.

The same protocol is repeated for the Leschaux boundary condition. Unfortunately, the ice flow velocities through the Leschaux gate are only available for the year 2003 from satellite data (Berthier and Vincent, 2012). For other years, we assume that the ratio $u_{s\mathrm{TAC}}(t)/u_{s\mathrm{TAC}}(2003)$ obtained from Tacul observations is similar for the Leschaux gate. Note that in 2003, the surface velocity at the Leschaux gate is small ($9\ \mathrm{m\,a^{-1}}$) compared to the velocity at the Tacul gate ($140\ \mathrm{m\,a^{-1}}$). Its maximum ice thickness ($175\ \mathrm{m}$) is half of that of Tacul gate ($360\ \mathrm{m}$) while their widths are similar ($\approx 1000\ \mathrm{m}$). The corresponding flux is consequently two orders of magnitude lower and its effect on the Mer de Glace flow is negligible during the period of interest. Therefore, for the forecast simulations, we simply assume that the thickness linearly decreases between the 2015 thickness and a null thickness in 2050. The velocity profile is then directly given by Eq. (6) without estimating a flux from the upstream accumulation.

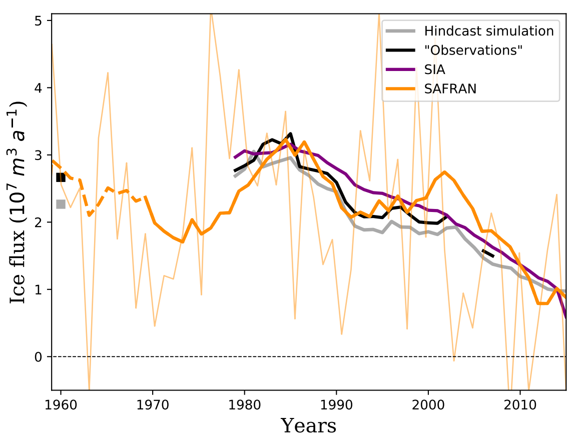


**Figure 3.** Ice flux through the Tacul gate from 1979 to 2015 based on a previous estimate (Berthier and Vincent, 2012, in black), from the SIA using only observed ice thicknesses at Tacul gate ( ~~orange~~purple), as imposed for the hindcast simulations (gray, see text) and compared to the yearly Safran surface mass balance integrated upstream of the Tacul gate (thin ~~green~~orange) and its 11-year running mean (thick ~~green~~orange).

## 4 Results

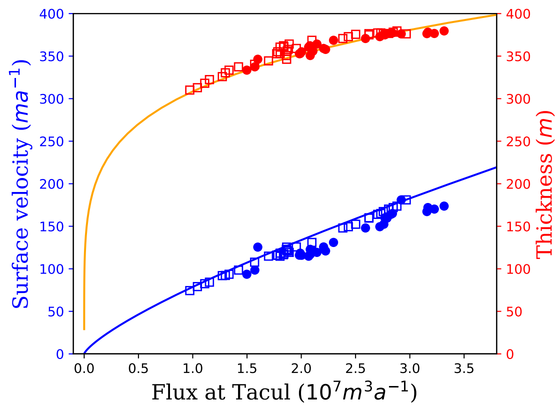


**Figure 4.** Surface velocity (blue) and thickness (red) at the Tacul gate as a function of the flux through the gate. The curves are the analytical solutions obtained using the SIA ~~diagnostic formulation~~ (Eq. (6)), the squares correspond to the flux integrated by Elmer/Ice using observed surface velocity, ice thickness and a velocity distribution given by Eqs. (4) and (5). The circles are the fluxes estimated by Berthier and Vincent (2012).

Figures 5 and 6 show, respectively, the reconstructed surface velocity, elevation and front position for the whole period. Results from the hindcast simulation are compared to the observations over the period 1979-2015. After this validation stage, the forecast simulations explore the range of possible evolutions corresponding to the 26 EURO-CORDEX climate scenarios.

### 4.1 Hindcast simulation

For the validation of the hindcast simulation, the results of the model are compared with the observed surface elevation changes (Fig. 5a) and centerline ice velocities at the four cross sections (Fig. 5b). Note that at ~~for~~ the highest observation ~~profile~~ (Tacul), the observations are used to impose the ice flux on this boundary of the model domain, explaining the perfect match between observations and model outputs. The validation is therefore only discussed for the three lowest profiles of Trélaporte, Echelets and Montenvers.

The overall ~~good~~ agreement of the model with the observations at the three lowest profiles was obtained without any tuning of the model parameters, except the inversion of the friction coefficient using the 2003 velocity and surface elevation dataset. The model is capable of reproducing the thickening phase in the first years of the simulation period with increasing ice velocity and ice thickness, as well as the subsequent thinning phase with decreasing surface elevation and velocity. Despite this ~~good~~ overall agreement, small differences are observed for both surface elevation and velocity.

For example, the peaks of calculated surface elevation and velocities are reached with a delay of about 3 years at Trélaporte. On the lower cross sections, Echelets and Montenvers, the surface elevation did not show a significant increase between 1979 and 1990. In general, the lower the profile, the larger the delay between the onset~~start~~ of the decrease of the simulated compared to ~~the~~ observed surface elevation. For all three of the lower cross sections, the modeled glacier is in general too thick over the last 25 years of the period compared to observations, with a maximum difference of up to 25 m for Montenvers, the lowest cross section. For this cross section, this overestimation decreases in the last years before 2015, eventually becoming an underestimation. In general, the hindcast shows that the response time of thickness and velocities is too long, indicating that the modeled glacier does not respond quickly enough to the flux changes observed at the Tacul gate. The possible causes for this response delay are presented in the Discussion section.

Despite these local differences in surface elevation and velocity, the general trend of snout retreat is very well reproduced ? by the model over the whole hindcast period (Fig. 6). The simulated front is almost stable between 1979 and 1990 and starts to retreat slowly 5 years before the observed retreat in 1995. Over the period 1995-2015, the observed rapid observedretreat of the ice front is well reproduced with a retreat rate of 30 $\mathrm{m\,a^{-1}}$ compared to 35 $\mathrm{m\,a^{-1}}$ for the observations.

### 4.2 Forecast simulations

The forecast simulations were carried out using the surface mass balance calculated from the 26 climate scenarios obtained in the framework of the EURO-CORDEX program (Fig. 2). Note that, all whatever the representative concentration pathway (RCP 2.6, 4.5 or 8.5) , all these scenarios lead to a very similar mean decrease in surface mass balance until 2050 at Tacul gate (see Fig. 2a), with an almost doubling of ice lost in 2050 compared to 1960. Large differences between the pathway scenarios appear only after 2050 (not shown). As a direct consequence, the same trend is observed for the integrated surface mass balance above Tacul gate (see Fig. 2b). Even if a few individual scenarios from all RCPs can lead to stable or even increasing integrated surface mass balance above Tacul gate until 2050, the general trend for all three RCPs is a decrease of surface mass balance, and therefore of the ice flux at Tacul gate which that can drop to close to zero in 2050.

All forecast simulations show significant thinning and slowing downstream of the Tacul gate (Fig. 5). At Trélaporte and Echelets cross sectionsgate, the differences of thickness changes are within the range of $\pm 20$ m and $\pm 10$ m, respectively, until 2030. Between 2020 and 2030, the thinning at Echelets profilegate is from 8.0 to 8.8 $\mathrm{m\,a^{-1}}$ (to be compared to the 5.0 $\mathrm{m\,a^{-1}}$ observed between 2005 and 2015). After 2030, the simulations show much larger differences induced only by the differences in surface mass balance obtained from the different climate scenarios. Note that each climate scenario influences both the ice flux through the Tacul gate and the surface mass balance over the modeled domain. At the Tacul gate, depending on the climate scenario, the surface elevation could be either stable or could decrease by 250 m in 2050. For the most pessimistic climate model of RCP 8.5 scenario (RCP 8.5), the remaining ice thickness at Tacul gate is only $\approx 80$ m in 2050, whereas the most optimistic scenario leads to a thickness slightly greater than that observed in 2015 (330 m).

However, these strong differences in ice thickness and ice flux at the Tacul gate lead to much smaller absolute differences in thinning and ice flow velocity downstream of the gate: the lower the cross section, the smaller the response differences for the different scenarios. For instance, modeled thinning at Trélaporte only varies in a range of 2 $\mathrm{m\,a^{-1}}$ between 2030 and 2040, to be compared to differences as large as 9 $\mathrm{m\,a^{-1}}$ at the Tacul gate over the same period. Despite some scenarios indicating stable conditions at the Tacul gate, surface elevation and ice flow velocity at the three lowest profiles decrease until 2050 for all whatever the climate scenarios, indicating highly unsteady state conditions far from steady state for the present glacier.

Our modeling results make it possible to ~~assess~~estimate the retreat of the snout over the next decades (Fig. 6). The observed rate of retreat was $35\ \mathrm{m\,a^{-1}}$ for the hindcast period 1995-2015. According to the forecast simulations, the terminus of Mer de Glace ~~glacier~~ will retreat at~~with~~ rates varying from $60$ to $85\ \mathrm{m\,a^{-1}}$ between 2020 and 2030, $65$ to $95\ \mathrm{m\,a^{-1}}$ for the period 2030-2040 and more than $90\ \mathrm{m\,a^{-1}}$ after 2040. As a consequence, the Montenvers cross section could be free of ice by 2023 and the Echelets cross section by sometime between 2031 and 2035, depending on the climate scenario (Fig. 6). For the most pessimistic scenarios, the terminus could be close to the Tacul gate by 2050.

Finally, we define a mean reference scenario constructed as the average of all 26 climate scenarios. Figure 7 presents the evolution of the ice thickness and the glacier extent for this mean reference scenario. It also illustrates the variability in glacier extent induced by the different climate scenarios until 2050 by showing the minimum and maximum extent obtained with the 26 different scenarios at year 2015, 2025, 2040 and 2050. This mean reference scenario is further used to study the relative contribution of ice flux at Tacul gate and surface mass balance of the glacier tongue in the Discussion section.

### 4.3 Sensitivity experiments

In order to test the goal is test the influence of the artificial flux condition at Tacul gate in our forcast we perform a set of sensitivity experiments. We run a reference scenario that corresponds to the mean of the 26 scenarios (e.g. mean surface mass balance and mean flux at Tacul gate). The trends obtained for this reference scenario are general and apply to most of the other individual scenarios presented above. We perform 3 additional simulations assuming either a constant surface mass balance with the value from the year 2015, a constant flux at Tacul gate (value from year 2015) or assuming that both surface mass balance and flux at Tacul gate are constant and equal to their 2015 values. The results are presented in Fig. 8.

## 5 Discussion

The model reproduces the evolution of the glacier over the past four decades relatively well. However, the observed timing and amplitude of changes are not perfectly reproduced and are increasingly inaccurate as the distance to the Tacul gate~~boundary condition~~ increases. In particular, the modeled glacier is too thick and velocity too high, resulting in a flux that is increasingly too high at the profiles of Trélaporte, Echelets and Montenvers. For the hindcast period, there is a relatively high level of confidence in the applied surface mass balance and imposed flux at Tacul gate~~boundary condition~~, both being directly derived from a continuously maintained network of stakes over the whole glacier. According to Thibert et al. (2008), we can expect uncertainties on ~~for the~~ ablation estimated from a network of stakes of the order of $0.15\ \mathrm{ma^{-1}}$ in ice equivalent thickness, which is low relative to the mean ablation measured on the tongue of Mer de Glace (from 5 to 12 $\mathrm{ma^{-1}}$). Other uncertainties arise from the linear extrapolation of ablation over the tongue (Eq. (3)) based on measurements in an area of clean ice. Indeed, debris cover has increased in recent decades and may have locally decreased ablation by up to $3\ \mathrm{m}$ (see Fig. 3b in Berthier and Vincent, 2012). This probably explains our overestimation of the thinning rate at the Montenvers profile after 2000 (see Fig. 5b).

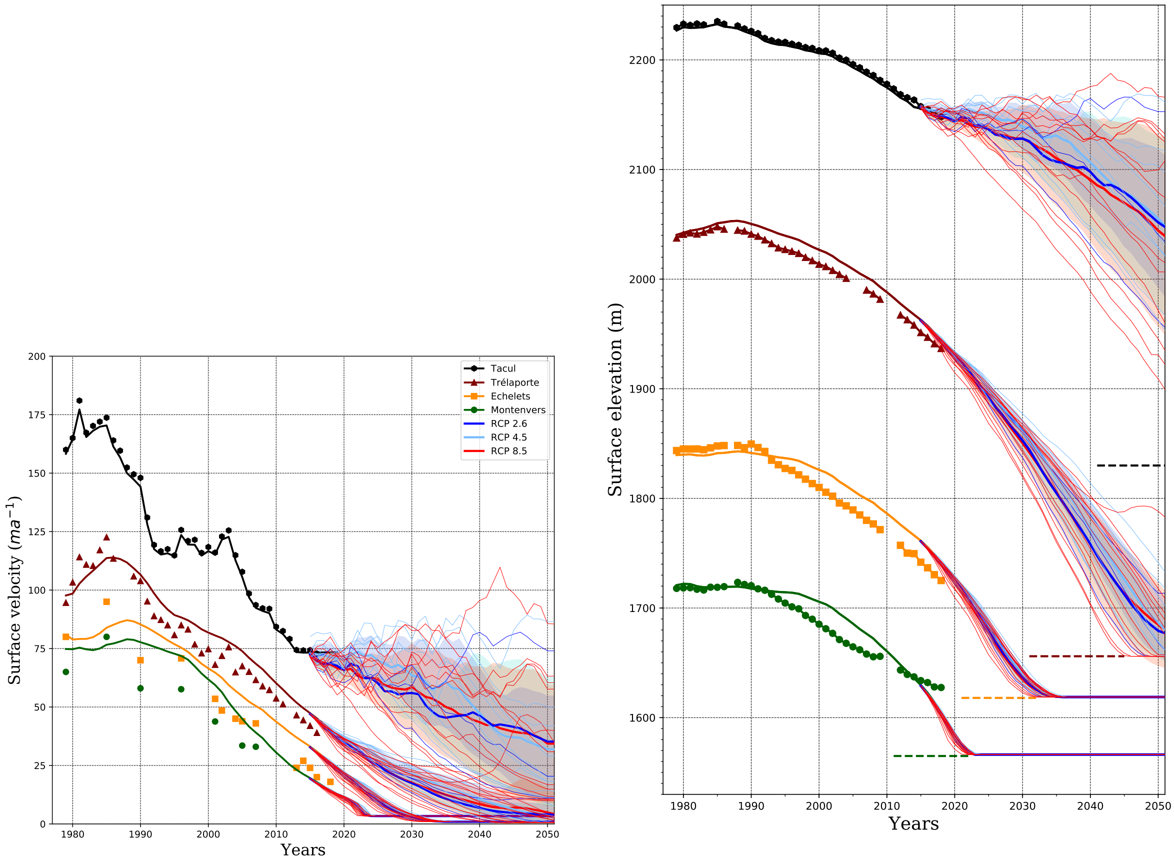


**Figure 5.** Surface velocity and surface elevation for all prognostic simulations. Hindcasts at the 4 profiles are shown by blark (Tacul), brown (Trélaporte), orange (Echelets) and ?green? (Montenvers) curves and the symbols are the corresponding observations. Forecasts are shown in in dark blue (RCP 2.6), blue (RCP 4.5) and red (RCP 8.5), with the average forecasts represented by thick curves with 1 $\sigma$ uncertainty bands (colored area). Dashed lines indicate the bedrock elevation for the 4 profiles.

The bedrock elevation, of ~~for~~ which measurements have ~~been~~ greatly improved by ~~due to~~ a recent radar campaign over the modeled area (unpublished), is also well ~~known~~constrained with an estimated average uncertainty of 10 m (Vincent et al., 2009). Moreover, velocities are not systematically over or under-estimated during the hindcast period, which might be an indication of~~for~~ a missing transient process in our simulation. Consequently, the major process explaining these discrepancies is likely basal friction and its evolution from year to year, not accounted for in the model. Indeed, the basal conditions are inverted from the 2003 dataset and kept constant over the whole simulation. Changes in glacier geometry and surface runoff have likely induced changes in basal conditions over the four decades. Inferring these changes would require contiguous surface DEMs and surface velocity maps, which are not available for dates other than 2003.

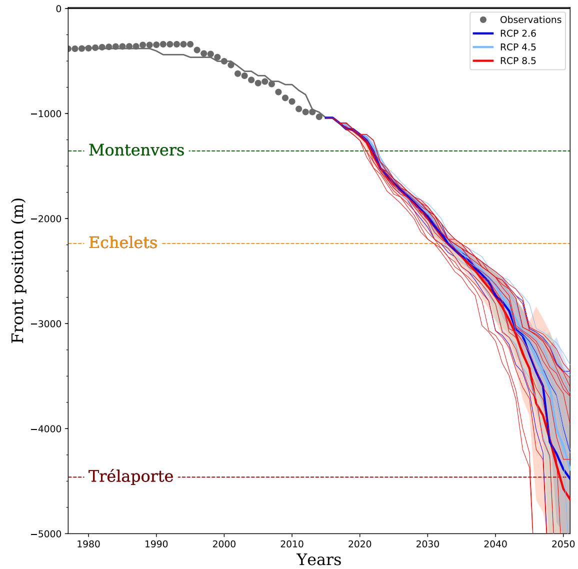


**Figure 6.** Evolution of the front position (along a flowline defined by the front fluctuation). The hindcast is in grey, and the squares represent observations. Forecasts are shown in dark blue (RCP 2.6), blue (RCP 4.5) and red (RCP 8.5) with 3 extreme scenarios underlined with thick curves and average forecasts represented by thick curves with 1 $\sigma$ uncertainty bands.

Regarding the glacier retreat, Berthier and Vincent (2012) estimated that over the period 1979-2008, two-thirds of the increase in the thinning rates observed in the lowest part of Mer de Glace was caused by reduced ice fluxes (and consequently emergence velocities) at Tacul gate and one third by increasing~~rising~~ surface ablation. In other words, they estimated that the retreat of the glacier front was more influenced by changes at high elevations than local changes. With a comprehensive ice flow description for the four last decades as well as for the future, the relative contribution to glacier retreat of local versus higher elevation changes can be quantified. The results of our hindcast are consistent with the result of Berthier and Vincent (2012) over the period 1979-2008. For the future, we run a reference scenario that corresponds to the mean of the 26 scenarios (e.g. mean surface mass balance and mean flux at Tacul gate). The trends obtained for this reference scenario ~~are general and~~ apply also to most of the other individual scenarios presented above. Contrary to the past trends, Fig. 8a clearly indicates that the future retreat of the glacier front will be influenced more by local changes (i.e. changes in surface mass balance over the lowest part of the glacier) than by changes in ~~of~~ flux from the upstream area (i.e. flux at Tacul gate). It is only after 2045, when the front approaches the Tacul gate, that its retreat starts to be largely influenced by changes in the upstream flux. The same trend is visible for surface elevation changes at the two lowest profiles of Echelets and Montenvers where changes in surface elevation are mostly influenced by the local surface mass balance (Fig. 8b). For the intermediate profile of Trélaporte, the influence from the flux at Tacul gate is visible, but the local surface mass balance still dominates the observed decrease of surface elevation over the whole studied period.

When surface mass balance is integrated over the glacier~~ whole glacier surface located~~ downstream of the Tacul gate, we can estimate the relative contributions over time of the surface mass balance and the flux at the Tacul gate to the total change in volume of the glacier tongue. As depicted in Fig. 9, surface mass balance and flux at Tacul gate were almost equal (in absolute value) over the period 1979-1994 and the glacier tongue of the Mer de Glace was very close to equilibrium, explaining an almost stationary front position over this period (Fig. 6). Nevertheless, since that period, both terms have started to decrease, but not at the same rate, explaining the two-third s contribution of flux at Tacul gate observed by Berthier and Vincent (2012) over the period 1979-2008, and confirmed by our results. Whereas the flux at Tacul gate has been ~~is~~ decreasing at an almost constant rate since the mid-1980s, the rate of decrease of the tongue-integrated surface mass balance is evolving with time. As shown in Fig. 9, the tongue-integrated surface mass balance is currently reaching its minimum and ~~will start~~ is expected to increase in the future. As a consequence, the volume lost from the tongue of Mer de Glace is currently reaching its maximum and ~~will~~should start to decrease in the future. Indeed, even if larger melt rates are expected in the future, the tongue-integrated surface mass balance is increasing toward zero due to the decrease of the glacier tongue area. This explains why the surface mass balance over the glacier tongue is increasingly dominating changes in ice volume downstream of Tacul gate relative to ice ~~the~~ flux through ~~at~~ the gate.

Because of the ~~adopted~~ model domain was restricted to ~~the part of~~ the glacier area downstream of the Tacul gate, it was not possible to conduct simulations after 2050 for most of the scenarios. Indeed, after this date, the ice thickness at Tacul rapidly decays to zero ~~becomes null~~. The choice of adopting a restricted domain for the modeling was dictated by the lack of measurements of ~~the~~ bedrock elevation upstream ~~in the upstream part of the Mer de Glace~~. Prognostic simulations over a longer period would therefore require ~~to acquire such data or to infer the~~ bedrock topography to be determined by additionnal mapping and/or inference using an inverse method (e.g. Fürst et al., 2018; Farinotti et al., 2019). Nevertheless, as shown by our ~~the sensitivity results~~, the evolution of the glacier tongue is not sensitive to the ~~this artificial~~ boundary condition imposed at Tacul gate. Therefore, including the upper part of the glacier in the modeled domain would not likely change the results for~~over~~ the studied period, but would allow simulations beyond ~~further estimates after~~ 2050.

Studies simulating the 3-D geometry of a mountain glacier have been performed by other researchers. Most studies focused either on past or future evolutions. To validate the hindcast studies, the authors generaly compare length reconstruction and area or volume and area when DEM are available (Jouvet et al., 2011; Zekollari et al., 2014) Our studies allows a yearly comparaison of thickness and velocity changes at different locations of the glacier. The iconic status of the Mer de Glace and facilites of the Electricité De France for hydropower resources and Compagnie du Mont Blanc for tourist activities justifiy a specific study with a state-of-the art model. Touristic facilites will have to modified.

Vincent et al. (2014) used a parametrized model calibrated with past thickness changes to simulate the future fluctuations of the MdG. They found that the MdG will retreat by 1200m until 2040. Zekollari et al. (2019) used a SIA model to reconstruct the evolution of all glaciers located in the Alps. They also used EUROCORDEX ensemble scenarios. They found that between 2017 and 2050 Mer de Glace will retreat from 2 to 6 km which is close to our results.

Jouvet and Huss (2019) lead a forecast for Great Aletsch Glacier with a full stokes model and the EUROCORDEX ensemble, the largest glaciers in European Alps, their results, also similar to Zekollari et al. (2019), predict a glacier retreat by around 5 km between 2017 and 2050.

This future evolution can also be related to the glacier response time which has been a subject of interest of several studies. The response time of glaciers are affected by several predictors such as the glacier size, the glacier SMB and glacier slope which is the main driver. Recently, Zekollari et al. (2020) used large scale glaciers modelling to investigate the response time in the European Alps. For Mer de Glace the relation proposed by the authors gives a response time of 60 years, which is typical of the range of European Alps glaciers ($50 \pm 28$ years). In our sensitivity experiment the future simulation performed with values flux at Tacul and SMB stationary after 2015 shows that the Mer de Glace will reach a steady state after 70 years and a front retreat of 4.1 km.

## 6 Conclusions

In this study, the Elmer/Ice ice-flow model was applied to simulate the past and future evolution of the lower part of the Mer de Glace ~~glacier~~. Given that the bedrock elevation remains unknown in the upper part of the glacier, we specified the ice fluxes at Tacul and Leschaux gates which are the upper limits of the tongue. These ice fluxes were obtained from monitored cross section surface area and ice flow velocities for hindcast or assessed from the simulated surface mass balance in the accumulation zone for the forecasts.???

The simulation of the glacier tongue for the period 1979 to 2015 was driven by (i) surface mass balance measurements and (ii) the ice flux at Tacul and Leschaux gates that were obtained directly from the observed section surface area and ice flow velocities. Ice flow modeling results were ~~accurately~~ compared to detailed and continuous observations of surface elevation, surface velocity and snout fluctuations over four decades during which the glacier both experienced a period of increase and a long period of decay. To our knowledge a comparison to data at this detail is unprecedented. We found that Elmer/Ice is able to reproduce the general behavior of the glacier. For example, the early growth of the glacier occurring between 1979 and 1990 is correctly reconstructed. However, the elevation increase is underestimated in the lower part of the tongue. After 1990, the modeling results are in agreement with observations. We suspect that the small differences between the model and the observations arise ~~could come~~ from the ~~assumed~~ constant basal friction parameter imposed~~conditions~~ over the hindcast period. Additional uncertainties on the surface mass balance of the tongue are likely related to the sparse debris cover.

Using 26 climate scenarios, the model was run forward to simulate the evolution of the glacier tongue until 2050. There were major differences in the ice fluxes calculated at the Tacul gate from all these scenarios, however changes in velocity and elevation at the lowest part of the glacier, as well as the retreat of the glacier front, were shown to be relatively independent of this upstream flux. Indeed, our sensitivity study indicated that the future changes at the lowest cross sections of the tongue are mainly influenced by the local surface mass balance, depending on the distance from the upper gate where the ice flux is presecribed ~~assessed~~. This also explains why the upper cross section of Trélaporte is more sensitive to the upstream flux condition at Tacul. ??? Because of the decreasing surface area, the loss of ice volume from ~~of the part of~~ the glacier downstream of the Tacul gate is currently reaching a maximum and will continue decreasing in the future. The glacier snout could retreat by 2 to 6 km over the next three decades and be close to Tacul gate in 2050.

Forecast simulations over a longer period would require extension of the model domain upstream of the Tacul gate, hindered by the unknown bedrock topography. Radar measurements in the upper part of the Mer de Glace and/or inverse modeling are therefore required to estimate the bedrock topography in this area before realistic forecast simulations of the Mer de Glace can be extended beyond 2050.

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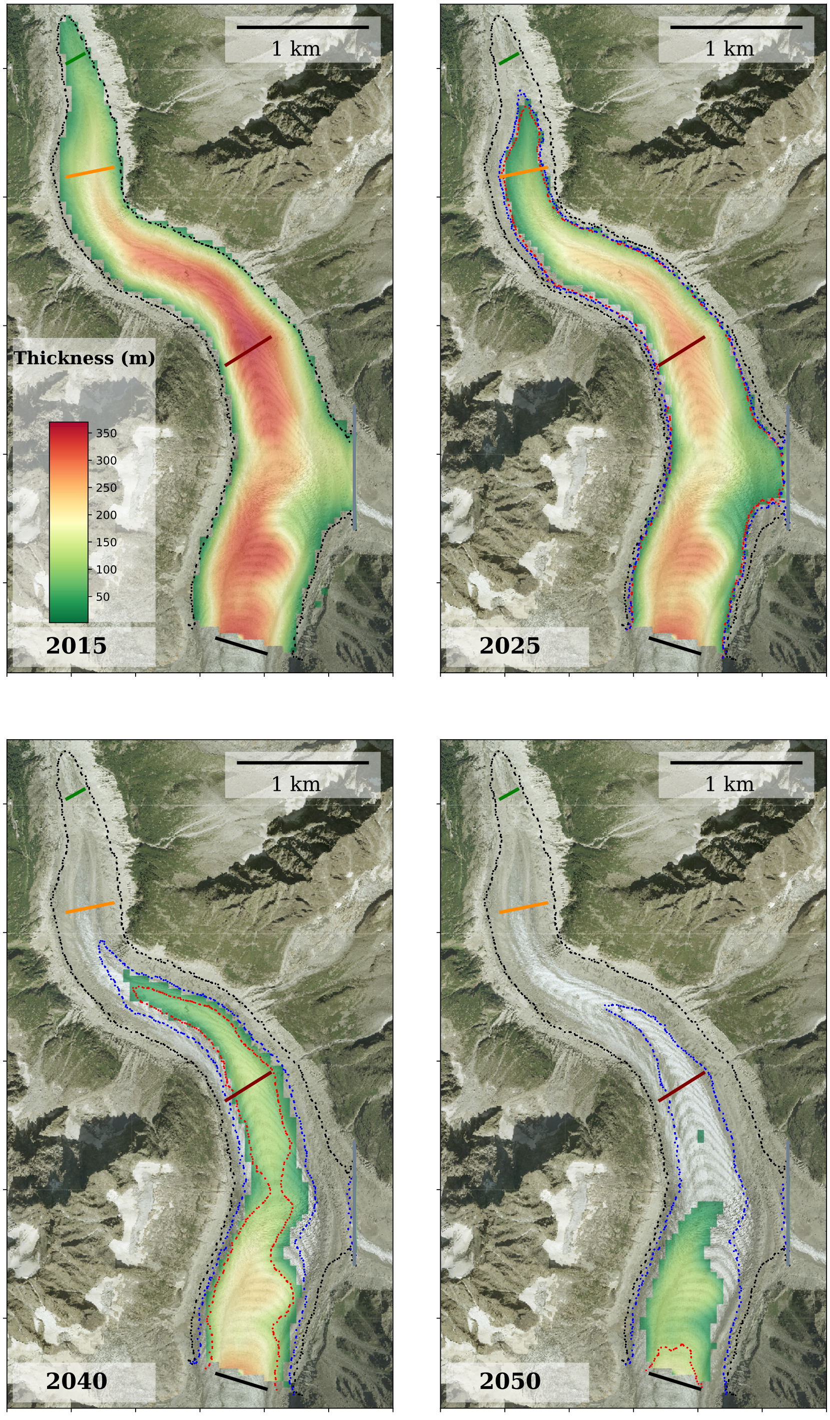


**Figure 7.** Ice thickness and glacier extension a) at the end of the hindcast simulation in 2015 and for the mean reference forecast simulation in year b) 2025, c) 2040 and d) 2050. The climate scenario for the mean reference forecast simulation is the average of all 26 climate scenarios. Extensions of the most optimistic and most pessimistic scenarios are plotted in dark blue and red, respectively. The initial glacier extension in 2015 is plotted in black. The background image is the orthophotoplan from 2008 (©RGD74).

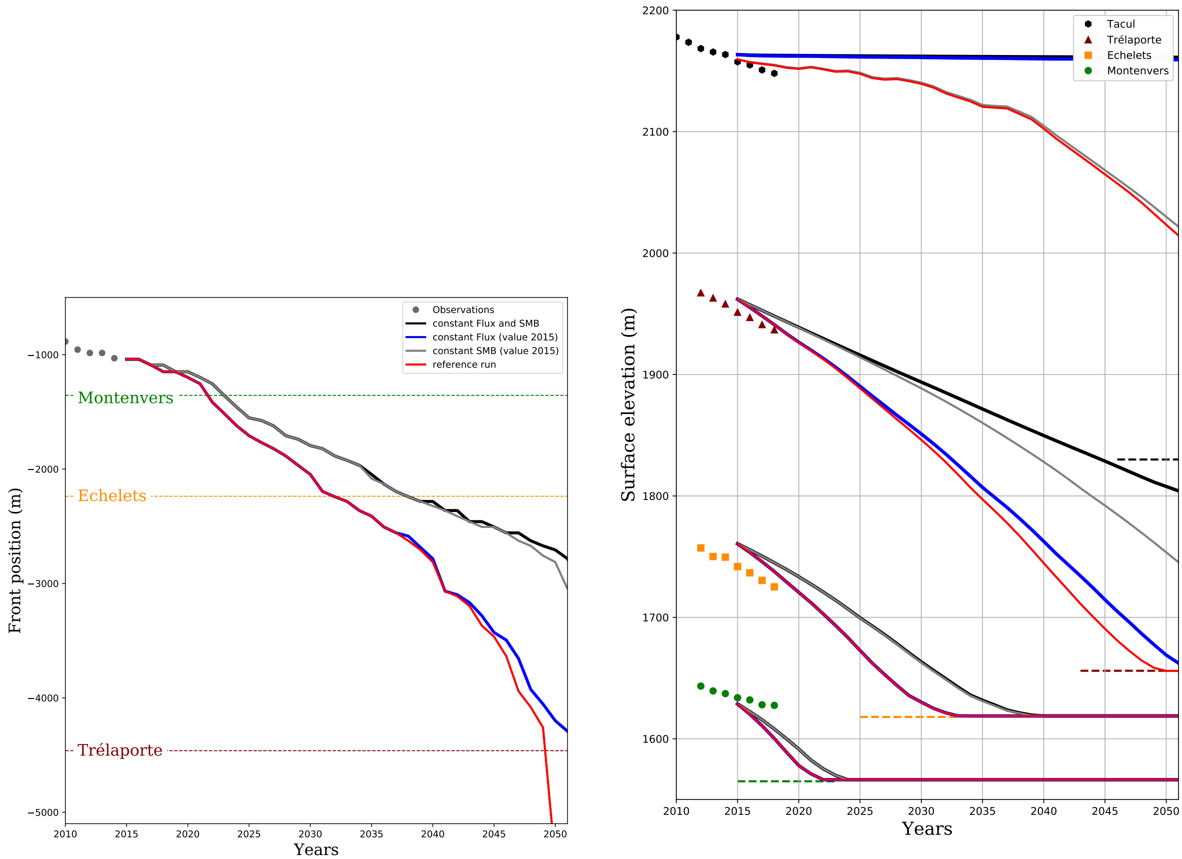


**Figure 8.** Sensitivity experiment for the mean reference scenario assuming the mean surface mass balance of all scenarios. Evolution of a) the glacier front and b) the surface elevation for this mean reference scenarios (red), assuming a constant surface mass balance (grey, value from year 2015), assuming a constant flux at Tacul gate (blue, value from year 2015) and assuming that both surface mass balance and flux at Tacul gate are constant and equal to their 2015 values. Dashed lines indicate in a) the position along the retreat line and in b) the bedrock elevation for the 4 profiles. For the two lowest profiles of Echelets and Montenvers, the red and blue curves are superimposed.

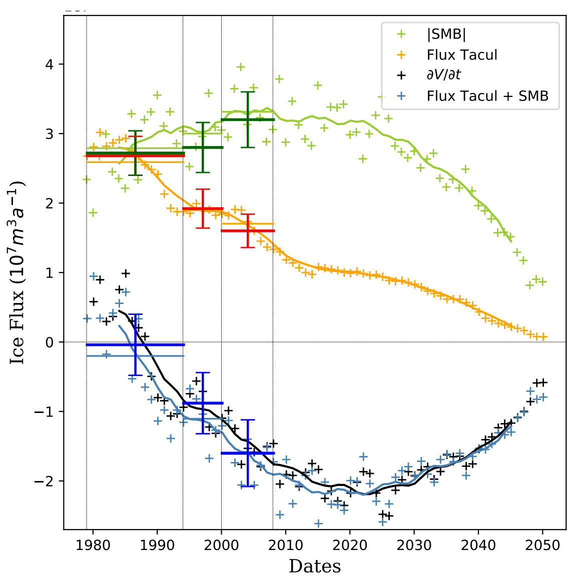


**Figure 9.** Sensitivity experiment for the mean reference scenario assuming the mean surface mass balance of all scenarios. Evolution with time of the absolute value of the integrated surface mass balance (green, real value always negative), integrated flux at Tacul gate (orange, always positive) and changes of volume of the glacier tongue (black) in cubic meters of ice per year. The blue curve represents the sum of the two fluxes and is almost equal to the change in volume. For each quantity, crosses represent annual values whereas the curve is a 10-year running average. The bars with error bars in dark colors are the estimates of the same quantities by Berthier and Vincent (2012) for the 3 periods delimited by the vertical gray lines. Horizontal lines using the same colors as the curves represent the averages of the different quantities over the same periods.