

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 #2

Dear Referee #2,

We thank you for your review. Your numerous comments in the original text were very appreciated and improve the readability of the text.

We do not explicitly answer to the editorial suggestion (i.e. corrections of the text) in this response but we included all them in the corrected version. We respond here to the main comments you have mentioned in the notes you included in the PDF.

Main structure changes of the manuscript

As the ice flow description belongs to the methods, the structure of the manuscript was slightly modified. 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.

We indicate also the position of our corrections in the PDF that contains our modifications.

Response to main comments

The significance of this study stems in part from the iconic status of the Mer de Glace, its historical significance and its prominent modern role as a tourist destination. With little extra effort, the authors could interpret the significance of their results in this context and add some interest and value to the paper that a broad readership would appreciate.

We agree that the iconic status of the Mer de Glace make this study significant and may interest readers beyond the scope. Parts of the article are rather technical but we tried to improve the discussion to interpret the significance of our results and address a broader readership. As said, the structure was simplified and the model description was lightened in the same purpose.

Though not a show-stopper for publication, it would be nice to see at least some comment on the sensitivity of the results to (1) the large precipitation correction factor and (2) the treatment of ice flux from the Leschaux gate.

The correction factor for precipitation is important (+70%) but this value is not surprising as models use to underestimate the amplification of precipitation at high altitude. We consider the uncertainties on precipitation are within the range covered by the 26 climatic scenarios.

To calibrate our PDD model, we looked at different values for the melting factors and for the correction factor for precipitations. Once chosen the melting factors (values from Réveillet et al. 2017) we determined the correction factor for precipitations to best fit SMB observations at Tacul gate (see Fig 2.) and on the accumulation area above 3000 m a.s.l. (not shown in our article). The value of 1.63 was found for the SAFRAN reanalysis. For the GCM-RCM couples the averaged value was 1.70. These values (1.63 and ~1.70) are similar as the climatic scenarios are corrected for the Alps by the ADAMONT method (Verfaillie 2017) using the SAFRAN reanalysis.

On the tongue, the correction factor has few, if none, influences as the ablation dominates the SMB. Averaged SMB is ~-5 m a⁻¹ at Tacul and ~-10 m a⁻¹ at Montenvers gate.

We use this factor to calculate the SMB on the accumulation basin (i.e. above the Tacul gate). This factor influences the integrated SMB we use to calculate the flux at the Tacul. Nevertheless, as future fluxes at Tacul gate are imposed relatively to their value of 2015: the absolute values are normalized and have no direct influence on the flux.

Thus, the influence of the correction factor for the flux at Tacul gate is limited to the rate of flux variation. For instance, in a scenario of monotonic decrease of the SMB, the lower the correction factor, the sooner integrated SMB will become null. As shown in Fig. 2b that presents the 11 years moving average integrated fluxes above

Tacul gate, our future scenarios spread the whole possible trajectory from the constant flux up to zeros as earlier as 2030. So, we can conclude that the choice of this parameter does not influence our results.

The treatment of Leschaux gate is very similar to the Tacul's one but as the flux through Leschaux gate is one hundredth smaller (estimated in 2003) than the one at Tacul we can assume that the sensitivity to this boundary condition is negligible after the 2000's. It may be less obvious in the 80's and we take this into account as we have implemented a similar behavior at both gates, the velocity and thickness at Leschaux being driven with the relative evolution of the velocity and thickness at Tacul.

We decided to avoid making the text more cumbersome with the description of this boundary condition briefly presented in the 'Methods' (see l.7-15 p.9).

I have made numerous comments (the review effectively) in the attached pdf that I hope will assist the authors with revisions, including editorial suggestion intended to improve the readability of the text.

We really appreciated your editorial suggestions that improved the readability of the text.

Line by line answer of the along-the-text comments

Abstract: Too sweeping. If referring to only European Alps, write "Alpine". Not all glaciers worldwide are shrinking and retreating.

We modified the first sentence by "*Alpine glaciers are shrinking and rapidly lose mass in a warming climate".*

Abstract: "We found that the model accurately reconstructs the velocity and elevation variations of this glacier despite some discrepancies that remain unexplained." Can this be quantified or made more precise in some way? We did not see which result would be the most significant and representative of the "accuracies" and/or "discrepancies" to be included in the abstract.

l16 p2: seems reasonable just to use the name of this glacier "Mer de Glace" rather than adding "glacier" at the end.

Excepted the first occurrence in the abstract, in the main text, we systematically refer to the glacier name as "Mer de Glace" without adding "glacier" at the end.

l16 p2: "as the glacier presents a large expansion before the eighties followed by a rapid retreat over three decades".

You suggested to modified the sentence ("presents a large expansion"). This is the rare suggestion we did not follow.

l6 p3: would be nice to give elevations here

(see l.10 p.3) We added the elevation of the four profiles.

L16 p3: The ice-flow model seems part of methods, especially since Mer de Glace-specific information appears in this section. & l1 p6: See earlier comment: ice-flow model seems it should be part of methods. SMB and input flux seem more like "Inputs" or "Boundary conditions" than a comprehensive description of study "Methods".

As answered earlier, we have modified the structure of the document. We merged the two sections "ice flow model" and "methods" in a single section 3 "Methods".

l16 p3: reference? Cuffey and Paterson? "e" is kind of junky notation for a paper. Suggest $\times 10$.

The reference for viscosity (Paterson 1994) was added, and the unit has been changed and $A=158 \text{ MPa}^{-3}\text{a}^{-1}$.

p6: Eq (7) something seems wrong with this equation. Intercept is missing and balance gradient (db/dz) should be dimensionless, not [1/m].

(old Eq (7) now Eq (3)) was effectively wrongly written. We forgot a sign '+', it is $\mathbf{b}(\mathbf{t}) = \mathbf{b}_{\text{tac}}(\mathbf{t}) + \mathbf{k}_b * (\mathbf{z}_S - \mathbf{z}_{\text{tac}}(\mathbf{t}))$.

l10 p7: The lack of sophistication of the classical DD model seems out of step with the sophistication of the ice-flow model and the volume of data available. I'm not suggesting this be changed here, but some better justification (aside from "simplicity and relatively good performance) should be provided. Has an enhanced temp-index model been tried (eg Hock, 1999) and shown not to yield improved performance? Do the timescales involved warrant use of the simplest possible SMB model?

We added a reference on the works of Réveillet et al. 2017 on which we rely. Their "results support the use of a classical DD model for long-term simulations of glacier-wide MB results support the use of a classical DD model

for long-term simulations of glacier-wide MB". Three decades (until 2050) may be considered as shorter term, but the evolution meteorological variables will be unknown, in particular local wind, turbulent flux, etc. which increase uncertainties.

l15 p7: Is there a rain-to-snow threshold used?

The rain-to-snow threshold is based on temperature and is 0°C.

l32 p7: In all cases, for the vertical evolution over the artificial boundary, we assume that the form of the vertical profile of the normal velocity is given by the Shallow Ice Approximation

See l24p7 the sentence has been changed to "In all cases, we assume that the form of the vertical profile of the horizontal velocity normal to the flux gate is given by the Shallow Ice Approximation."

Figure4: In the legend, "SIA diagnostic formulation" is replaced by "SIA".

l8 p11: Please quantify at least some of these subjective assertions of "good agreement" and "very well reproduced".

"despite this good overall agreement": "good" was removed.

We think that the following sentences describe the behavior of the model and the differences with the velocity and thickness observations:

"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..."

"the general trend of snout retreat is very well reproduced":

We think that the following sentence describes the behavior of the model and the differences with observations of the front:

"The simulated front is almost stable between 1979 and 1990 and starts to retreat slowly 5 years before the rapid observed retreat in 1995. Over the period 1995-2015, the observed rapid retreat of the ice front is well reproduced with a retreat rate of 30 m a⁻¹ compared to 35 m a⁻¹ for the observations."

l22 p11: gate = cross sections = profiles, right? Choose one.

This is right. We replaced 'cross sections' and 'profile' by 'Gate' (see l.12 to 14 p.11).

Discussion: I have to say that I'm somewhat disappointed not to read anything about the social implications of the demise of MdG. One of the reasons this study is valuable is because of the iconic status, historical significance and tourist attraction of MdG. Can you say anything about, e.g., what the results might mean for the local community or how much more difficult it will be to access the MdG from Montenvers than it was in historical times, or whether this makes the ski tour from the AdMidi more/less safe, doable, etc?

We'll add a new paragraph in the discussion to compare our results with other studies (not finalized).

The retreat of the glacier will have an impact on the access to the tongue, and some hydropower or touristic facilities will have to be modified. We'll try to add a sentence on the local impact for the users of the Mer de Glace if possible.

Concerning the skitour, the increasing ablation will probably prevent use during late spring. It is difficult to predict the evolution of the ice fall without simulating the glacier du Géant and conclude on its influence on skitour feasibility.

Vincent Peyaud, on the behalf of the co-authors.

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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Corrections 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
5 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
10 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 length 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
15 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
20 (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; 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). 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; Jouvét 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 km². 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 m a.s.l. From this accumulation region, the ice flows at speed up to 700 ma⁻¹ rapidly through a narrow, steep portion (an icefall between 2700 and 2400 m a.s.l.) before feeding the lower, 7 km long section above the terminus part of the glacier down to a front located at 1534 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 m a.s.l.) from a network of stakes maintained that are monitored continuously since 1979 at four different elevations: the Tacul (2148 m a.s.l. in 2018), Trélaporte (1937 m a.s.l.), Echelets (1725 m a.s.l.) and Montenvers (1627 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 m a.s.l. using mechanical borehole drillings, seismic soundings (Süstrunk, 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

OLD SECTIONS 3 AND 4 NOW IN METHODS. MESH IN SUP. MATERIAL.

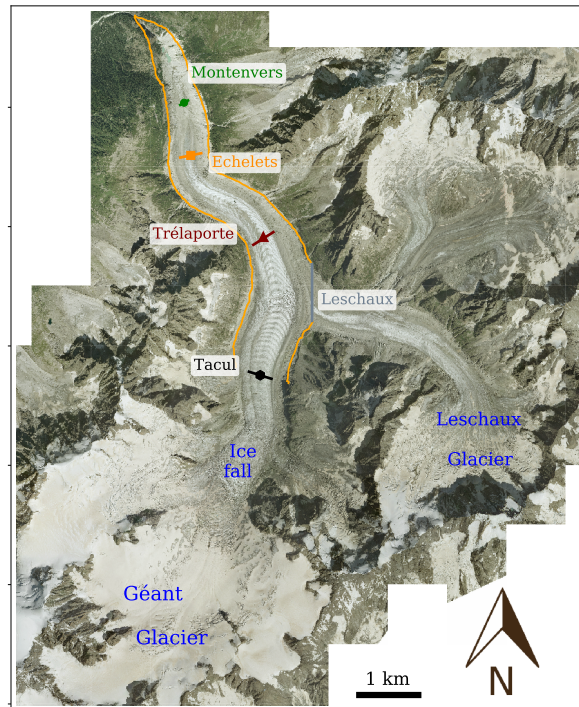


Figure 1. Map of Mer de Glace (orthophotoplan acquired in 2008 ©RGD74). Orange contour delimits the area modeled in this study. The location of the four cross sections (Tacul, Trélaporte, Echelets and Montenvers) and the Leschaux gate are indicated by the colored lines. The Tacul and Leschaux gates represent 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 $\mathbf{u} = (u, v, w)$ and p , the isotopic pressure, are solutions of the Stokes equations that express 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 ($A = 158 \text{ MPa}^{-3} \text{ a}^{-1}$, Paterson, 1994). Indeed, the ice of the lower part of the Mer de Glace glacier is most likely temperate (Liboutry et al., 1962).

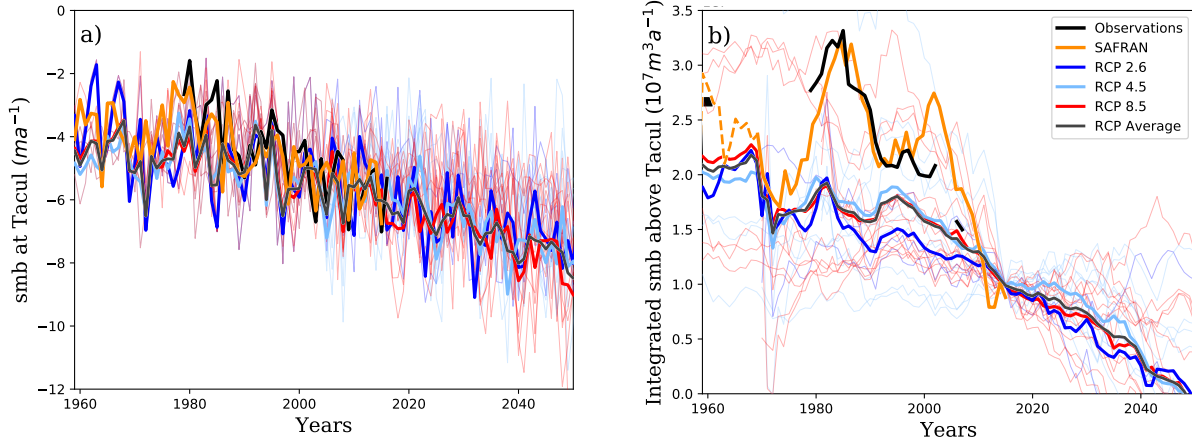


Figure 2. Evolution with time from 1960 to 2050 of a) the surface mass balances (SMB) at Tacul gate and b) the integrated surface mass balance above Tacul gate. Observations are presented in black and values inferred from SAFRAN in green. The others climate scenarios are plotted in dark blue (RCP 2.6), 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:

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

where the surface mass balance $b(z, t)$, in ice equivalent thickness (m a^{-1}), is a function of surface elevation and time and

- 5 $\mathbf{u}_s = (u_s, v_s, w_s)$ 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 [areglacier](#) is a temperate glacier, a certain amount of sliding on its bed is expected. A linear friction law relating the basal shear stress τ_b

- 10 to the basal velocity \mathbf{u}_b is applied on the lower boundary:

$$\tau_b + \beta \mathbf{u}_b = 0. \quad (2)$$

The [time-independent](#) 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.

5 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
10 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 ~~areannual~~ surface mass balances, surface velocities and elevation changes are available yearly at the four cross sections of Tacul, Trélaporte, Echelets and Monteners (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~~
15 ~~hindeast 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 (hindeast 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
20 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:~~

$$25 \quad b(z_s, t) = b_{\text{TAC}}(t) + k_b [z_s(t) - z_{s\text{TAC}}(t)] , \quad (3)$$

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
30 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 $0.0048 \text{ mK}^{-1}\text{d}^{-1}$ for snow and $0.0053 \text{ mK}^{-1}\text{d}^{-1}$ 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

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

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

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

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

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

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

10 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 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
 15 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
 20 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
 25 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
 30 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 m. For surface velocity, a minimal condition of 10 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 $u_{s\text{TAC}}(t)/u_{s\text{TAC}}(2003)$ obtained from Tacul observations is similar for the Leschaux gate. Note that in 2003, the surface velocity at the Leschaux gate is small (9 m a^{-1}) compared to the velocity at the Tacul gate (140 m a^{-1}). Its maximum ice thickness (175 m) is half of that of Tacul gate (360 m) while their widths are similar ($\approx 1000 \text{ m}$). 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.

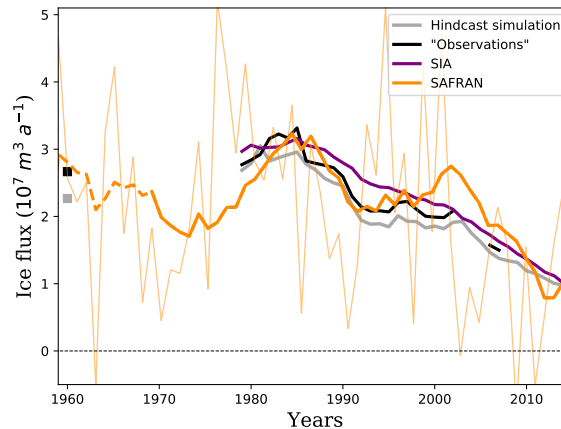


Figure 3. Ice flux through the Tacul gate from 1979 to 2015 based on a previous estimate (Berthier and Vincent, 2012, in black), from the SIA using only observed ice thicknesses at Tacul gate (orangepurple), as imposed for the hindcast simulations (gray, see text) and compared to the yearly Safran surface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

4 Results

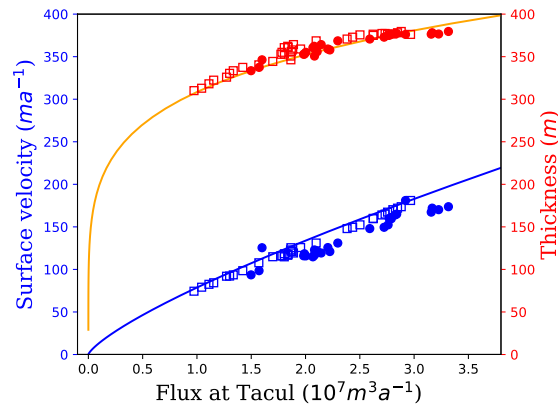


Figure 4. Surface velocity (blue) and thickness (red) at the Tacul gate as a function of the flux through the gate. The curves are the analytical solutions obtained using the SIA [diagnostic formulation](#) (Eq. (6)), the squares correspond to the flux integrated by Elmer/Ice using [observed surface 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

- 5 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.
- 10 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.
- 15 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 [onsetstart 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 retreat of the ice front is well reproduced with a retreat rate of 30 m a^{-1} compared to 35 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-sections gate, the differences of thickness changes are within the range of $\pm 20 \text{ m}$ and $\pm 10 \text{ m}$, respectively, until 2030. Between 2020 and 2030, the thinning at Echelets profile gate is from 8.0 to 8.8 m a^{-1} (to be compared to the 5.0 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 $\approx 80 \text{ m}$ 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 m a^{-1} between 2030 and 2040, to be compared to differences as large as 9 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 [assessestimate](#) the retreat of the snout over the next decades (Fig. 6). The observed rate of retreat was 35 m a^{-1} for the hindcast period 1995-2015. According to the forecast simulations, the terminus of Mer de Glace [glacier](#) will retreat [atwith](#) rates varying from 60 to 85 m a^{-1} between 2020 and 2030, 65 to 95 m a^{-1} for the period 2030-2040 and more than 90 m a^{-1} after 2040. As a consequence, the Montenvers cross section could be free of ice by 2023
5 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
10 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 forecast we perform a set of
15 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.

20 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 [gateboundary 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
25 confidence in the applied surface mass balance and imposed flux at Tacul [gateboundary 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 m a^{-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 m a⁻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,
30 debris cover has increased in recent decades and may have locally decreased ablation by up to 3 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](#)).

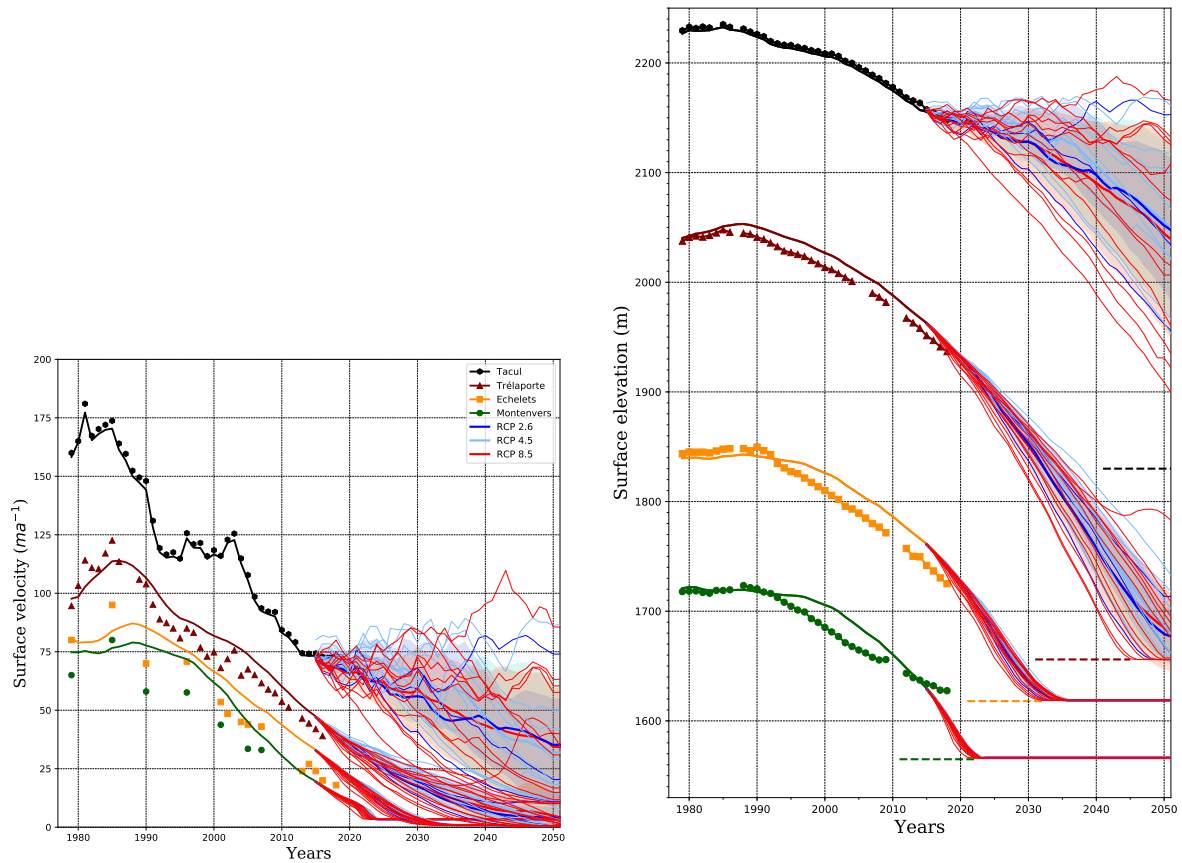


Figure 5. Surface velocity and surface elevation for all prognostic simulations. Hindcasts at the 4 profiles are shown by black (Tacul), brown (Trélaporte), orange (Echelets) and green (Montenvers) curves and the symbols are the corresponding observations. Forecasts are shown in dark blue (RCP 2.6), blue (RCP 4.5) and red (RCP 8.5), with the average forecasts represented by thick curves with 1σ 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 offer 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.

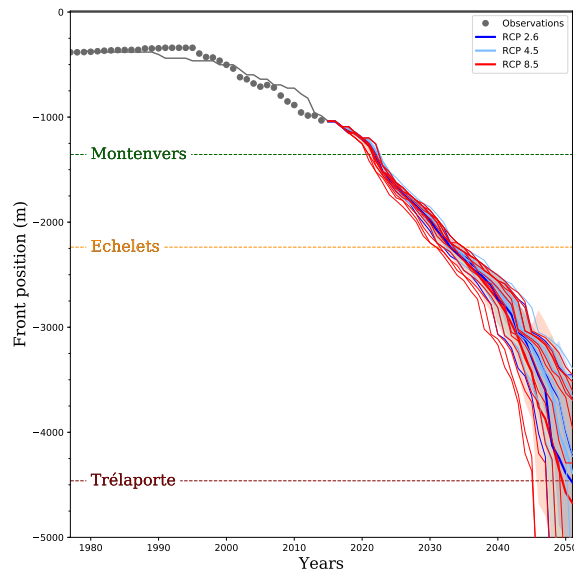


Figure 6. Evolution of the front position (along a flowline defined by the front fluctuation). The hindcast is in grey, and the squares represent observations. Forecasts are shown in dark blue (RCP 2.6), blue (RCP 4.5) and red (RCP 8.5) with 3 extreme scenarios underlined with thick curves and average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

5 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

10 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 Monteners where changes in surface elevation are mostly influenced by the local surface mass balance ([Fig. 8b](#)). For the intermediate profile of Trélaporte,

15 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 ~~willshould~~ 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 ~~forever~~ 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 generally 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 comparaisn 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 justify 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 ± 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

10 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.???

15 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.

25 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 prescribed 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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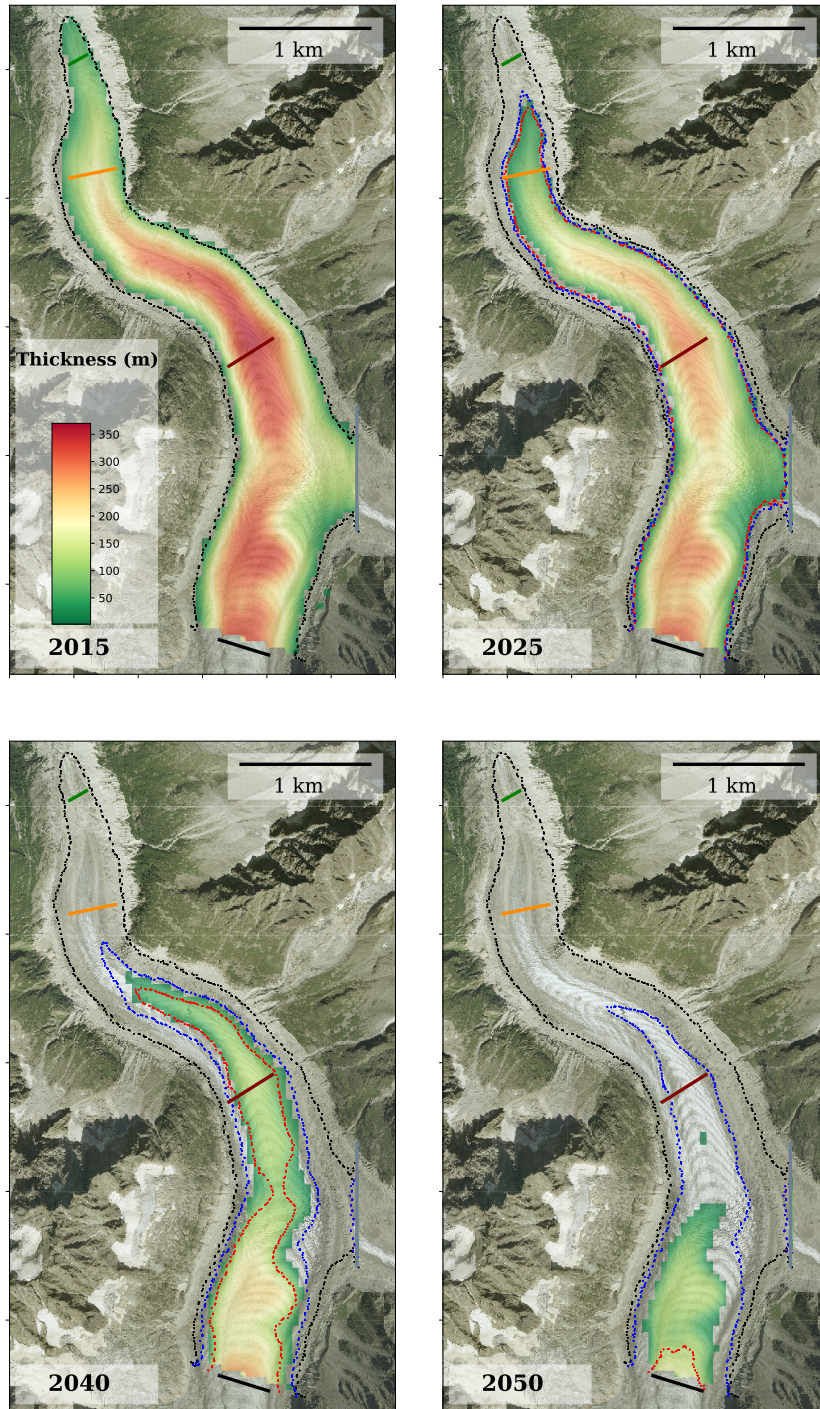


Figure 7. Ice thickness and glacier extension a) at the end of the hindcast simulation in 2015 and for the mean reference forecast simulation in year b) 2025, c) 2040 and d) 2050. The climate scenario for the mean reference forecast simulation is the average of all 26 climate scenarios. Extensions of 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).

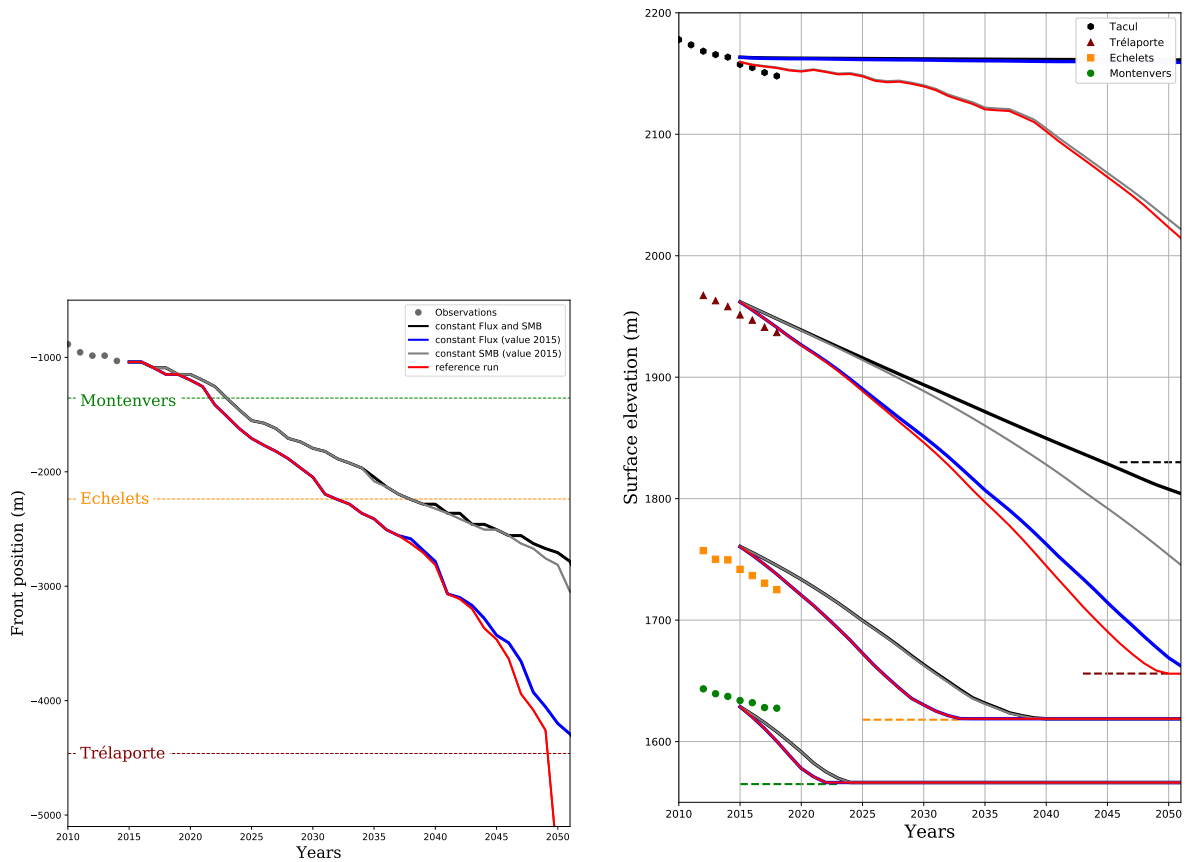


Figure 8. Sensitivity experiment for the mean reference scenario assuming the mean surface mass balance of all scenarios. Evolution of a) the glacier front and b) the surface elevation for this mean reference scenarios (red), assuming a constant surface mass balance (grey, value from year 2015), assuming 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.

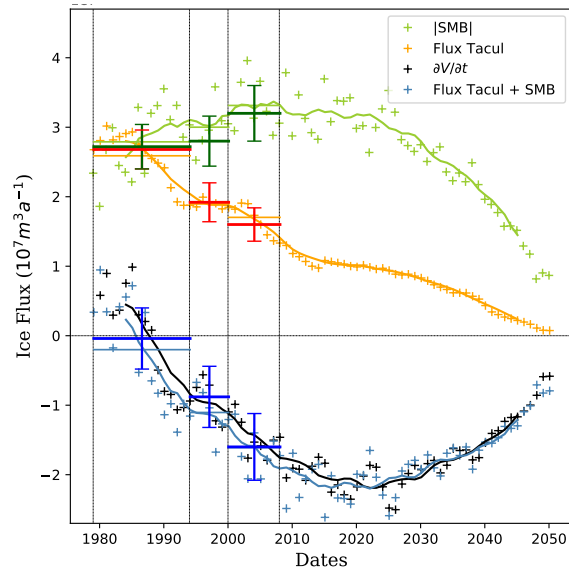


Figure 9. Sensitivity experiment for the mean reference scenario assuming the mean surface mass balance of all scenarios. Evolution with time of the absolute value of the integrated surface mass balance (green, real value always negative), integrated flux at Tacul gate (orange, always positive) and changes 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.