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 #3

Dear Referee #3

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

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.

General comments:

It is a pity to see that only the lower part of the Mer de Glace was modelled (as explained in section 3.2 and 4.2). While going through the manuscript, I was constantly thinking: why is this the case? The explanation, in which this is linked to the uncertainty in the bedrock, appears only towards the end of the manuscript (p.15, l.20-21). If you were to consider the upper part of the glacier also, you would indeed introduce additional uncertainty in your simulations; but you now also do so by imposing several conditions on the fluxes through the upper gates (Tacul and Leschaux): e.g. linking the flux at the gates with upstream integrated surface mass balance based on observations and imposing this for the future (while in reality the glacier response time will play a big role here). It would really be nice to see how much this influences your results by having some additional sensitivity tests in which you modify the imposed model settings. Even better would be to have some simulations in which you model the entire glacier (i.e. after inverting the ice thickness in the accumulation area) and see how they compare to your results. Would this be feasible? Such a test would require some additional work, but I honestly think that this would add a lot to your story and would also increase the impact of your story (as it could be used as a kind of reference for future studies that impose fluxes at gates and only model a part of the glacier – a method that may definitely gain in popularity for certain applications!)

We agree it would be more satisfactory and impressive to have modeled the whole Mer de Glace up to its accumulation basin. Unfortunately, measurements of the bed are very parse upstream the Tacul Gate, and inexistent on the Lechaux Glacier. We choose to concentrate on the lower part where a large dataset exists.
By the way, strictly speaking, Mer de glace is restricted to the name of the tongue of the glaciers downstream the merging of Tacul and Leschaux glaciers. To alert the reader, in the introduction (see l.34 p.2) we added a mention to “the tongue” of the Mer de Glace:

> *“to reconstruct these past multi-decadal fluctuations* ***of the tongue of the Mer de Glace****”.*

The Tacul boundary condition is well constrained by observation during the hindcast period. In the case of using a reconstructed dataset, uncertainties are also very large. For example, the reconstruction of Huss and Farinotti 2012 of the Argentière Glacier underestimate thickness locally by a factor two (Rabatel et al. 2018). Only a careful calibration of upstream surface mass balance and dynamics (viscosity/sliding) may constrain correctly the flux at Tacul. In all cases we have to inverse the sliding, using the observed velocity of 2003. Thus, we would have a couple thickness/sliding calibrated with one observation at Tacul gate. This calibration would be kept constant for the forecast simulations. The discussion of the relative uncertainties of the two methods could be a part of another study. We add a mention to this point in the perspective.

The level of detail of your analyses is very sophisticated and you consider several elements in your evaluation and for the projections that many other studies do not include.

- o However, it would also make sense to have insights in the more widely considered glacier characteristics, such as glacier volume and area:

§ For past: with this you can directly assess the performance of your model to reproduce e.g.:

• Past volume changes (would in fact be a kind of test for your surface mass balance model in this case), which can be derived from DEM differencing (and which I imagine is maybe already directly available for this glacier?).

• Past area changes.

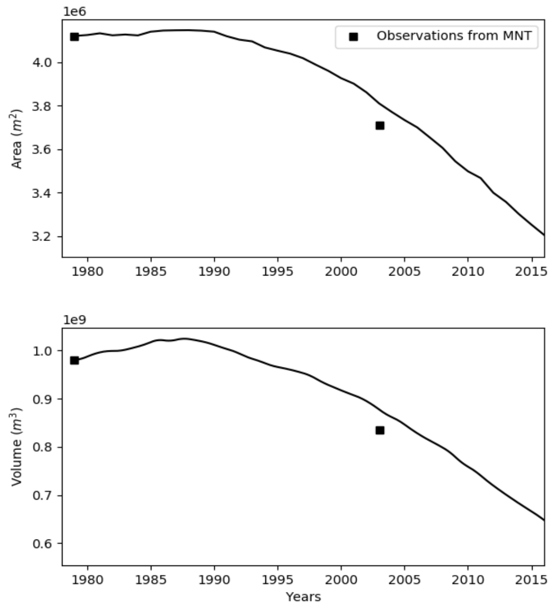

Fig R3-1: Area and volume evolution for the hindcast simulation.

We plotted the area and volume evolution for the hindcast simulation (See Fig R3-1). Comparisons with the few MNTs available show a good agreement. The Fig. 5 showed that we overestimate the thickness. The new figure shows that the volume is also slightly overestimated (in 2003). The volume decreases between 1979 and 2003 (14% of the initial volume) is underestimated by 30%, extent reduction is also underestimated (10% of the initial area) is underestimated by 25%.
We will add this figure in the Supplementary Material.

§ For future: allows you to compare more easily to other studies in which the evolution of Mer de Glace is also modelled and comparison with other glaciers in the European Alps (e.g. is Mer de Glace more/less retreating than other glaciers...; list of studies is provided further on) In general, you refer to your study as an elaborate evaluation, which it definitely is, and which I think is very impressive. However, some of the agreement may also results from several choices you made, which are not always explained (see comment below on this). It is therefore difficult to disentangle which part of the agreement results from a kind of calibration ('tuning') and is therefore not a real kind of validation/evaluation (as you want the calibration and the evaluation data to be – ideally entirely – independent).
We added a comparison with results from other models in the discussion. We answer below to the point you have proposed to disentangle tuning from evaluation. We "acted" on the three boundary conditions (Flux at Tacul gate, sliding and SMB). No other choices influence the dynamics of the glacier at the four validation datasets (the three gates and the front).

• There is a sort of discrepancy between the complexity of the model used for the ice dynamics and the relatively rough approach for surface mass balance and imposed boundary conditions at the gates. Given that the glacier is so well studied, why did the authors not consider more complex approaches for this (e.g. thinking of e.g. debris cover; constant mass balance gradient)? A few additional sentences and motivation would be nice.
Yes, the use of an ice flow model with high complexity contrasts with the simple degree day approach for the surface mass balance (SMB) and the use of a constant and homogenous vertical gradient for SMB.
L.9 p.7 (now see l.9 p.7) 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 SMB". Three decades (until 2050) may be considered as shorter term, but the evolution of meteorological variables will be unknown, in

particular local wind, turbulent flux, etc. which increase uncertainties and render very complicated the use of a more sophisticated SMB model.

The Argentière glacier, situated also in the Mont Blanc moutain range is well more monitored, with an AWS on the side: it could be a good choice for future studies with more complex SMB model. But Mer de Glace cannot allow such validation of the SMB model. This is why we decided not to add debris cover influence in this study as it would be another “tuning” to explained the behaviour of the Montenvers evolution in the recent years (>2000). Below we add a sensitivity experiment on the SMB vertical gradient and also discuss the debris cover.

• Some assumptions are made, and it is not always clear how these affect your results. Would be good to have some additional insights in the sensitivity of your findings to your various assumptions. This includes assumptions related to:

- o Constant mass balance gradient
- o Imposed ratio between sliding and surface velocities at the Tacul gate
- o Assumption that relationship between ice flux at Tacul gate and integrated surface mass balance for upstream area remains the same
- o Minimal thickness and velocities at the gates
- o Linear decrease ice thickness at Leschaux gate over time,

For a full list and more details, refer to the specific comments below.
We answered your comment on these various assumptions in our responses below.

• Most of the figures could be improved relatively easily to enhance their readability: see suggestions below.
We modified the figures and describe the specific changes below.

Specific comments and suggestions

Abstract:

• p.1, l.2: ‘All alpine glaciers are shrinking and retreating at an accelerating rate...’: technically this is not entirely true. It is the case for most glaciers, but there are some exceptions (e.g. glaciers that are almost gone or those that disappeared; i.e. where the retreat does not accelerate). Suggest changing this to: ‘Alpine glaciers are shrinking and rapidly lose mass in a warming climate’
We replaced the first sentence of the abstract by your proposition.

• p.1, l.8-9: ‘To our knowledge a comparison to data at this detail is unprecedented’: indeed, a very detailed comparison to data is present, which is very nice. But not sure you can claim that it is unprecedented, as comparisons to other studies are not straightforward (in some studies other types of data have been considered). Probably best to remove from abstract and mention in this in the main text, where there is room for more nuance. Check studies on individual glaciers with elaborate evaluation and/or calibration with ground-truth data (e.g. Adalgeirsdóttir et al., 2011; Zekollari et al.,2014; Hannesdóttir et al., 2015).
We wrote that a “comparison to data at this detail is unprecedented” because this is “to our knowledge” the first comparison of a model with geometry and dynamics from yearly in-situ measurements. Most studies compare length variation, or volume variation when MNT are available, but rarely long-term local observations. We explained this in a new paragraph (not finalized) at the end of the ‘Discussion’.

• p.1, l.9-10: You mention the velocities and the elevation changes for the model evaluation. What about the mass balances and the length variation, which you mention a few sentences before (in l. 6): how do these perform? This becomes clear in the text, but for consistency would be good if you could already mention them here.
We added the fact that the model reproduces well the length variation.
By mass balance do you mean volume evolution? The mass balance is also well reproduced but we do not present it in our figures, so we do not mention it at this point.
The new sentence is:

“*We found that the model accurately reconstructs the velocity, elevation and length variations of this glacier…*”

1 Introduction:

• p.1, l.19: 'sea-level rise': could be worth referring to the new GlacierMIP studies, in which the future sea level contribution from glaciers are obtained from a community-wide intercomparison effort (Hock et al., 2019; Marzeion et al., 2020)
References to the new GlacierMIP studies (Hock et al., 2019; Marzeion et al., 2020) have been added.

• p.1, l.21-22: 'first studies': you are not very specific here. Given that you model a single glacier and have not mentioned the 'large-scale' glacier modelling aspect yet, one would assume that these are the first studies for the evolution of individual glaciers in the European Alps. I suggest being more specific here (mentioning the regional aspect) and/or to refer to pioneering studies in which ice dynamics are included for individual glaciers (e.g. Huybrechts et al., 1989; Letréguilly & Reynaud, 1989; Stroeven et al., 1989; Greuell, 1992). Would somehow be strange to spend your introduction focusing on largescale glacier modelling, while your work in fact focuses on very detailed glacier modelling.
We introduced the first studies of an individual glaciers to start the sentence that introduce the different possible methods (last studies cited are large scale). We add in the list for each method the first study you mentioned but we kept also the last one. Here are the new sentences:

"The first studies of an individual glaciers (e.g. Huybrechts et al., 1989; Letréguilly and Reynaud, 1989; Stroeven; Greuell, 1992) were restrained to flowline model related to the local driving stress while studies on regional scale (since Hae- berli 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; 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)."

• p.2, l.6: better also update with the new numbers from the second GlacierMIP effort (Marzeion et al., 2020)
The reference has been updated.

• p.2, l.10-12: list of references for 'model describing the complex three-dimensional geometry of a whole glacier' is a bit odd:

o Some studies do not take into account the glacier evolution over time

o Others are in fact based on the SIA, which makes them rather 2D (as described in the title of Le Meur & Vincent, 2003) and more in line with what you describe earlier (p.2, l.4-5) as 'Process-based model ... to take into account simple dynamics' (Clarke et al., 2015)

o The ITMIX experiment, which focuses on ice thickness reconstruction (Farinotti et al., 2017), is also a bit odd to mention here

o Why not simply focus on what you also do here: 3-D time-evolving simulation of a single glacier? (e.g. Schneeberger et al., 2001; Le Meur et al., 2004; Jouvet et al., 2009, 2011; Zekollari et al., 2014; Ziemen et al., 2016; Jouvet & Huss, 2019; Gilbert et al., 2020; Schmidt et al., 2020).

Would also be interesting for the discussion to compare your modelled future evolution of Mer de Glace with the modelled evolution of other glaciers in the European Alps (see also general comment on this).
We modified the sentence to focus on Full Stokes model and keep few of the most recent references:

Indeed, with the 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. Jouvet and Funk, 2019; Réveillet et al., 2015; Gilbert et al., 2020).

• p.2, l.21: 'This dynamics' à 'These dynamics'
That sentence was removed and the previous one was rewritten (see l.22-24 p.2).

3 Ice flow model:

• p.3, l.29: Value for the rheological parameter for ice: how was this value chosen? Quite often this is used as a calibration parameter as it has a large influence on the ice thickness (/glacier volume). By just taking a value from literature: difficult to assume that this will work well immediately for your glacier of interest. See studies in which this was analysed / where this rheological parameter was tuned (e.g. Schmeits & Oerlemans, 1997; Albrecht et al., 2000; Vincent et al., 2000; Giesen & Oerlemans, 2010; Adalgeirsdóttir et al., 2011). From my understanding, in your study the calibration occurs through the basal sliding, in which you try to match observed velocities: but what is effect of this approach on modelled ice thickness evolution? i.e. How are you sure that the modelled evolution

is related to physical forcing and not to some kind of model drift? Would be good if you could explain this a bit in the manuscript.
The reference for viscosity (Paterson 1994) was added, and the unit has been changed and A=158 $MPa^{-3}a^{-1}$.
We did not explore other value of viscosity. In that case we will add to inverse a new sliding. This would change the vertical deformation. This is a limitation of our study. We will discuss this limitation in the discussion part of the manuscript.
We have verified that there was no special drift of the model (due to discrepancy sliding2003/topography1979) at the beginning of the simulation.

• p.4, Figure 1: would have been nice to have surface elevation information in this figure (vs. visual imagery). Through this, would be easier to orient for someone who's not very familiar with the glacier.
We did not add altitudes in this figure but we wrote the elevation of the 4 profiles in the main text.

• p.5, l.16: model domain does not cover the entire glacier. Why? (I saw later that this is explained towards the end of the manuscript) Should really clarify this choice. Pity to not have the entire glacier in / or additional experiments in which this is the case to compare to,
This is already described at the end of the 'study site' but maybe not enough visible: this sentence is now a new paragraph (L.23-26 p.3, with text unchanged).

• p.5, l.28-29: 'Bedrock elevation...interpolation (Fan et al., 2005) of all available observations': does this mean that the bedrock is simply obtained from a kind of kriging? Is it not justified to rely on a more sophisticated approach, especially given the fact that you then use a very complex 3-D model to solve for dynamics and temporal evolution? Would also be good to have an idea where the ice thickness (/bedrock elevation) was measured (unpublished data is mentioned later; but maybe you can add the profiles in a figure somewhere?).
Bedrock elevation is obtained by kriging but the dataset is dense. The mesh subsection was moved to supplementary and we will give the location of the different radar profiles used to build this DEM.

4 Methods:

• Name of the section ('Methods') is maybe not ideal, as in fact the previous section ('Ice flow model') is also really part of the methods. As you mainly describe the boundary conditions here (at the cross sections), you could consider renaming this section 'Boundary conditions' or something alike?
As said earlier the 'Ice flow model' was merged with the 'Methods' section.

• p.6, Figure 2:

o Quite difficult to decipher this figure: the grey line, which represents the 'average' is barely visible in the right panel.

o Not ideal to combine green and red colours for lines in a single figure, given that a considerable amount of people cannot see the difference between these two colours (see e.g. https://en.wikipedia.org/wiki/Color_blindness#Red%E2%80%93green_color_blindness).

o One needs to look up in the caption what the average stands for, maybe specify that this is the average of the RCPs? Same of Safran: maybe good to specify this, as not clear what this is at this point in the manuscript (i.e. Reanalysis 'SAFRAN')

o Do not entirely get why you show RCP's for the past and how this should be interpreted. Makes sense that these are off if they have not been forced with reanalyses product (e.g. ERA5). With this, expect them to be much closer to SAFRAN reanalyses product also. Also, not entirely clear if what you show here is the SAFRAN original SMB, or the one that is corrected by scaling the precipitation with ca. +60-70% (as you describe towards the end of section 4.1.). I expect the latter, given the good agreement in SMB. If so, and if I understand it correctly, would it also make sense to have the 'modified' SMB (with precipitation correction) from the RCPs?

This figure was improved. We modified the RCP colours. We changed the green color for SAFRAN to orange to avoid mixing green and red. The gray line was slightly enlighted and is a bit more visible.
Indeed, the SAFRAN and the forecast scenarios values are the one that are corrected by scaling the precipitation with ca. +60-70%. As (i) the legend is long, (ii) the precipitation correction is one parameter of the SMB model and (iii) that model is described latter in the text we decided to keep the same text. We fear it would be more confusing to the reader.

• p.6, l.5-7: 'For the forecast simulations from 2015 till 2050, results from climate simulations are used to evaluate the flux on the different boundary conditions of the glacier domain': I get the meaning of this sentence, but it is a

bit strange / misleading to use ‘evaluate’ here, as this is what you use to describe the evaluation of the hindcast also. Maybe change to: ‘...are used to simulate the future flux evolution at the boundary of the glacier domain’
Changed to: ‘...are used to simulate the future flux evolution at the boundary of the glacier domain’

• p.6, l.6: ‘till’ à ‘until’
Done

• p.7, l.4-5: ‘Despite this strong variability from year to year (Fig. S1 in the Supplementary Material and Rabatel et al., 2005), a constant mass balance gradient of kb = 0.009 m^{-1} is adopted for hindcast and forecast simulations'. How does this affect your results / how would your result look like if you take into account the interannual variability and also not rely on a constant gradient?
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. R3-2 present the vertical gradient for SAFRAN and the run CLM_HadCEM_RCP45, which is representative of most simulations. The altitude of interest (1650 to 2250 m a.s.l.), in bold, shows an interannual variability of the gradient that we did not take into account.
We did not 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 that an averaged value would lead to similar results.

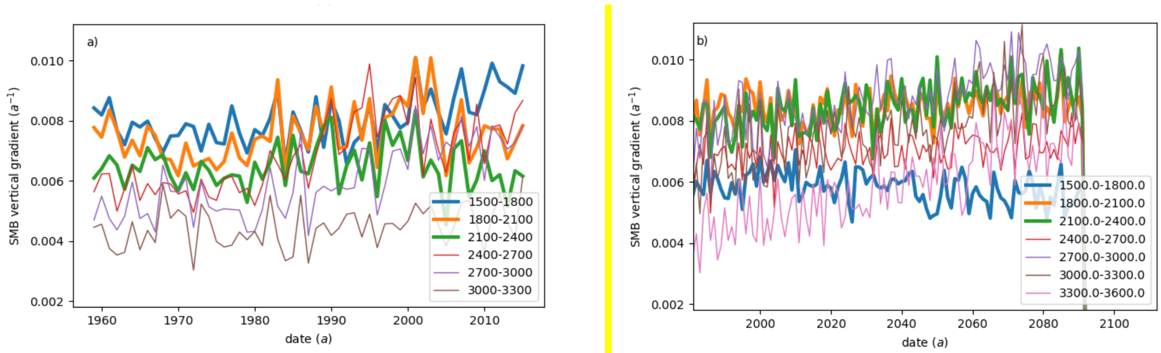

Fig. R3-2: *Vertical SMB gradient extracted from a) SAFRAN and b) a climatic scenario with our PDD method every 300 m. Meteorological variable are available every 300 m of altitude from 1500 to 3600 m a.s.l.: the gradients are calculated between each level and level at the altitude of Mer deGlace are in thick lines. Example given for CLM_HadCEM_RCP45.*

Nevertheless, we explored the sensitivity to the gradient of SMB. For SAFRAN the averaged gradient is 0.007 a^{-1}, lesser than the adopted value of 0.009 a^{-1}. For the climatic simulations, the value above 1800 m a.s.l. are similar to 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}, also lesser than the adopted value of 0.009 a^{-1}. The choice of these differents gradient (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 sets 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. R3-3 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.

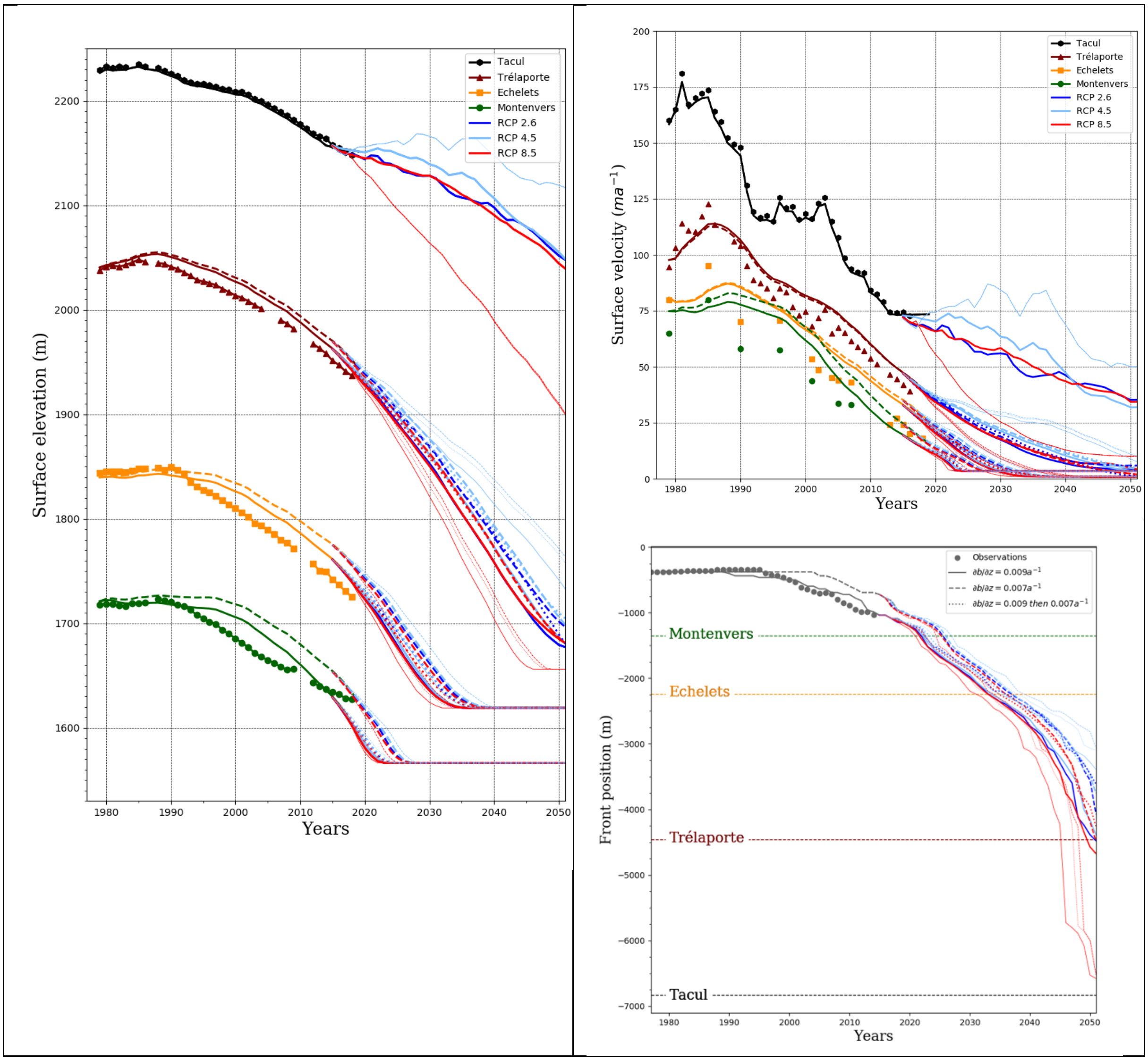

Fig. R3-3: *Altitude, surface velocity and front evolution for three scenarios with different SMB vertical gradient of 0.009 a^{-1} (solid lines); 0.009 for hindcast and 0.007^{-1} for forecast (dotted lines); 0.007 a^{-1} (dashed lines). Average RCPs scenarios are plotted with thick curves, the extremes scenarios with thin curves.*

• p.7, l.6-9: why did you consider these 26 future climate projections from the EURO-CORDEX ensemble, given that there's many more (>50) available? Any criterion used to choose only those? Moreover, are these simulations from the RCM at 0.11° resolution or at 0.44° resolution (or a mix?). Would be good if you could be a bit more specific on this.

The 26 future climate projections from the EURO-CORDEX ensemble belongs to the ensemble of regional climate projection that was adjusted with the ADAMONT method (Verfaillie et al., 2017). The RCM chosen are at 0.11° resolution (≈ 12.5 km).

The adjustment is described in Verfaillie et al. (2018): the authors assume that the 13 GCM–RCM pairs reasonably sample the overall uncertainty resulting from the 3RCPs (2.6, 4.5 and 8.5), even though not all EURO-CORDEX GCM– RCM combinations are available. The EURO-CORDEX raw surface fields were adjusted using the ADAMONT method, which is a quantile mapping and disaggregation method taking into account weather regimes to provide multi-variable hourly adjusted climate projections.

In the section "Surface mass balance" of the "Methods" we rewrote the sentence that describes the source of these climatic scenarios:

"*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, RCP45 and RCP8.5.*"

• p.7, l.34 – p.8, l.1: 'we further assume a constant and uniform ratio between sliding and surface velocities of 1/3 at both gates': what is this assumption based upon? Given the lack of direct observations of basal velocities, the uncertainty on this statement is quite large. How does this influence your results?
The factor was inferred to fit Berthier and Vincent 2012 estimation of the flux. The methods allow to have a realistic and "continuous" velocity field through the boundary condition. Downstream (on the next grid cells) the 3D velocity field adjust with the sliding coefficient. We performed some tests but what is important for the simulation is the total flux through the gate.
The sensitivity to this factor is low: with our velocity distribution, between a ratio of 0.2 and 0.5 the flux at the gate differs by only 0.2%.

• p. 8, l. 28-30: assumption about relationship flux at Tacul glacier and integrated surface mass balance higher area. You assume that this remains constant in the future: how much does this influence your results?
We have assumed that the relationship flux at Tacul and integrated SMB at higher elevation does not change. Indeed, the location of the Tacul gate is just downstream the ice fall where ice flow from the accumulation basin in less than one year (at speed up to 700 m a^{-1}). We expect a very rapid response of Tacul flux to flux that come from accumulation basin.
The sensitivity experiments test the influence of the artificial flux condition at Tacul gate and show that in the next decades the tongue is more sensible to the local surface mass balance.

• p.9, l.7: imposed values for minimal ice thickness and surface velocities. Why are these values chosen? And what is influence on your simulations?
These values are arbitrary. They correspond to a flux at Tacul of 2.10^5 m^3 a^{-1} (to be compared with the flux in 2015: 1.10^7 m^3 a^{-1}). The remaining minimal thickness at Tacul gate may stop the front retreat 300 m downstream the gate (6 grid points). However, as explained in the main text (see l.29-34 p.8) the minimal thickness (corresponding to the minimal flux) is reached by no scenarios by 2050. In few run a minimal value for the velocity is reached but we checked that this does not influence the front retreat. In our sensitivity experiments, we show that for the mean reference scenario, the integrated SMB (mass loss) is well above the flux though the Tacul gate (mass gain) in 2050 (see now Fig. 9). The former process dominates the evolution of the tongue. As mentioned in the text, this is why our forecast stop in 2050.

• p.9, l.14-15: linear decrease in ice thickness at Leschaux gate: again, sounds rather arbitrary. What is effect of this on your simulations? Can imagine that this could have quite an impact on projected future changes.
The effect of ice flux from Lechaux is negligible after 2015. As mentioned in the main text, we have estimated this flux with the 2003 observed surface velocity field. At this date the flux at Leschaux gate was two orders of magnitude lower than the one estimated at Tacul gate.
The influence of Leschaux tributary was one of our issue when we initiated this work but it occured that this gate had no significance on the result after the 2000's. It was 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.

• p.9, Figure 3 + p.10, Figure 4:
o Like for figure 2: would make sense to have information on what the different lines represent in the figure itself instead of in the caption. There is enough space, and would make the interpretation much easier and more intuitive (and an advantage if you plan on using this in a presentation later!)
Figures 3 and 4 were modified

Results:

•Although you do not really calibrate to this, it is not fully clear how the several choices you have made affected your simulations and can therefore be considered as an independent evaluation.
For the hindcast simulation, the parameters we calibrated are (i) the 2D sliding coefficient of the sliding law with the 2003 observed velocity field, (ii) the flux at the Tacul gate inferred from thickness and velocity in-situ observations and (iii) the surface mass balance given by ablation stakes measurements at Tacul gate and at different places on the tongue for the vertical gradient.
Surface mass balance and sliding calibrations include observations at the profiles where the model is evaluated but do not affect the transient ice flow response modeled by Elmer/Ice.

• p.11, l.1-2: 'In general, the lower the profile, the larger the delay between the start of decrease of the simulated compared to the observed surface elevation': this does not really come as a surprise, as you impose the fluxes at

the Tacul gates to fit observations. As such the uncertainty in your results ‘spreads’ as you go away from these points (towards lower glacier elevations).
Indeed, this sentence is just a description of the result.

• p.12, Forecast simulation: part of the similarity in future evolution is driven by the fact that the SMB is quite similar, as the difference in the forcing (temperature and precipitation) increases with time and in fact only becomes really notable during the second part of the 21st century. However, a part of this is also simply related to the glacier response time, which is in the order of decades for this glacier.
Would probably be worth placing this in context a bit (potentially in the discussion session) and making the link to response time studies on Alpine glaciers (e.g. Zekollari et al., 2020).
As the SMB are similar for all RCP until 2050 we clarify this point with a new sentence (l.14 p.11):

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

A new paragraph (not finalized) has been added in the discussion to compare our results with previous studies. News sentences can be included to introduce the response time:

“*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. Using the relation proposed by the authors Mer de Glace should react to climate change with a response time of 60 years, which is typical of the range of European Alps glaciers (50 +/- 28 years). In our sensitivity experiments, 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 in ~70 years after a front retreat of 4.1 km.*”

• Fig. 5-7: would again be good if could read the figure without having to refer to the legend (i.e. add information about the RCPs in figure directly). For RCP colours, it would be nice if you could use more conventional colours for the different RCPs (e.g. those used in the IPCC reports). Finally, mixing green and red in the same figure is still not a very good idea.
We modified the RCP colours and we changed the green color to avoid mixing green and red.

Discussion & conclusion:
• Nicely elaborated and very interesting in general!
Thank you, we appreciate that you find this discussion interesting.

• p.13, l.6-8: role of debris is mentioned. Given the complexity of your ice flow model and the level of detail of your analysis, would it not make sense to incorporate debris cover in your approach (and eventual evolution over time; see e.g. Jouvet et al., 2011)? Or maybe do some tests in which this is incorporated in a parameterized way to analyse whether this decreases the discrepancy between observations and modelling that you mention here.
The tongue of the Mer de Glace has an increasing debris cover, which is until now restricted over the last kilometer downstream the Echelets gate. We assume this 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 as conscious this could lead us to overestimated front retreat. The sensitivity experiment can this an insight into its influence.

Vincent Peyaud, on the behalf of the coauthors.

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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 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 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 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 (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

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

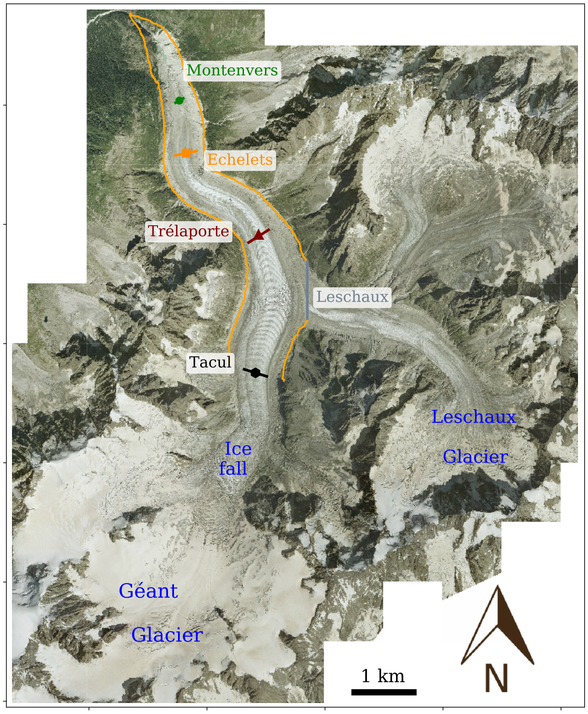

Figure 1. Map of Mer de Glace (orthophotoplan acquired in 2008 ©RGD74). Orange contour delimits the area modeled in this study. The location of the four cross sections (Tacul, Trélaporte, Echelets and Montenvers) and the Leschaux gate are indicated by the colored lines. The Tacul and Leschaux gates represent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

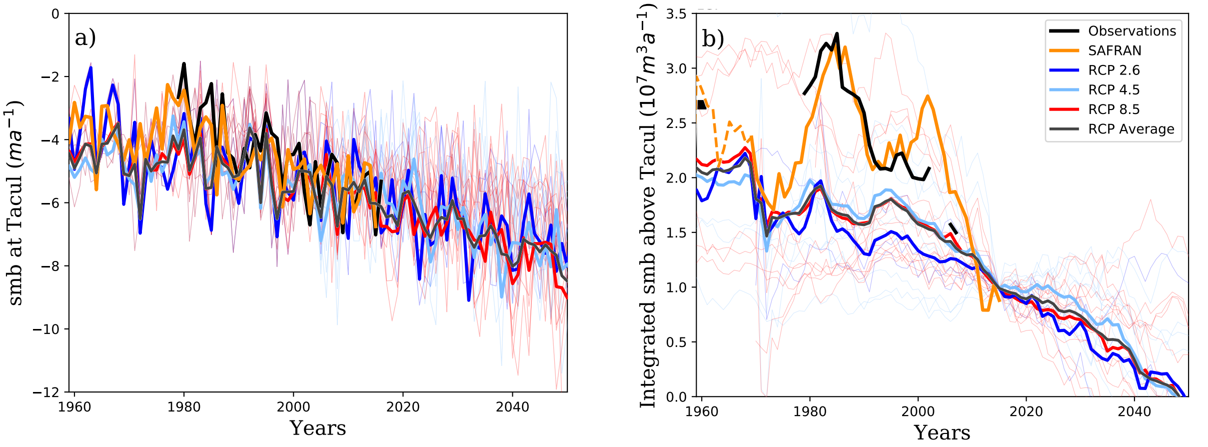

Figure 2. Evolution with time from 1960 to 2050 of a) the surface mass balances (SMB) at Tacul gate and b) the integrated surface mass balance above Tacul gate. Observations are presented in black and values inferred from SAFRAN in green. The others climate scenarios are plotted in dark blue (RCP 2.6),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

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

where $b_{\mathrm{TAC}}(t)$ is the annual surface mass balance measured (hindcast) or evaluated (forecast) at the Tacul altitude $z_{s\mathrm{TAC}}$. 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 $k_b = 0.009\ \mathrm{m}^{-1}$ 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 $k_b = 0.009\ \mathrm{m}^{-1}$ 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):

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

In the above equations, z_b is the bedrock elevation whereas H denotes ice thickness. In Eq. (6), the surface slope ∇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 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.

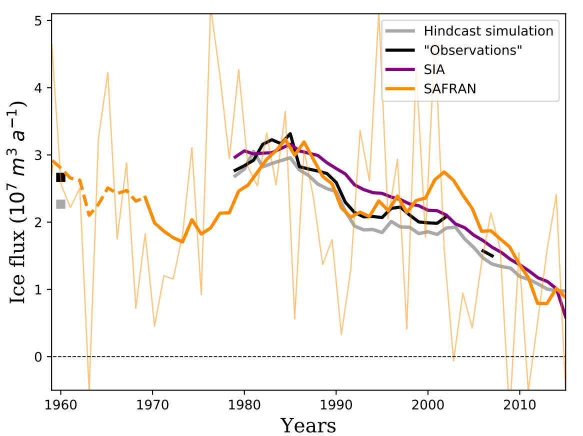

Figure 3. Ice flux through the Tacul gate from 1979 to 2015 based on a previous estimate (Berthier and Vincent, 2012, in black), from the SIA using only observed ice thicknesses at Tacul gate (~~orange~~purple), as imposed for the hindcast simulations (gray, see text) and compared to the yearly Safran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

4 Results

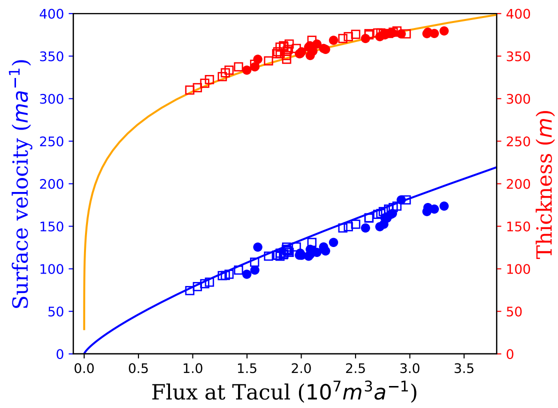

Figure 4. Surface velocity (blue) and thickness (red) at the Tacul gate as a function of the flux through the gate. The curves are the analytical solutions obtained using the SIA ~~diagnostic formulation~~ (Eq. (6)), the squares correspond to the flux integrated by Elmer/Ice using observed surface velocity, 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 sections~~gate, the differences of thickness changes are within the range of ± 20 m and ± 10 m, respectively, until 2030. Between 2020 and 2030, the thinning at Echelets ~~profile~~gate 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 ≈ 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).

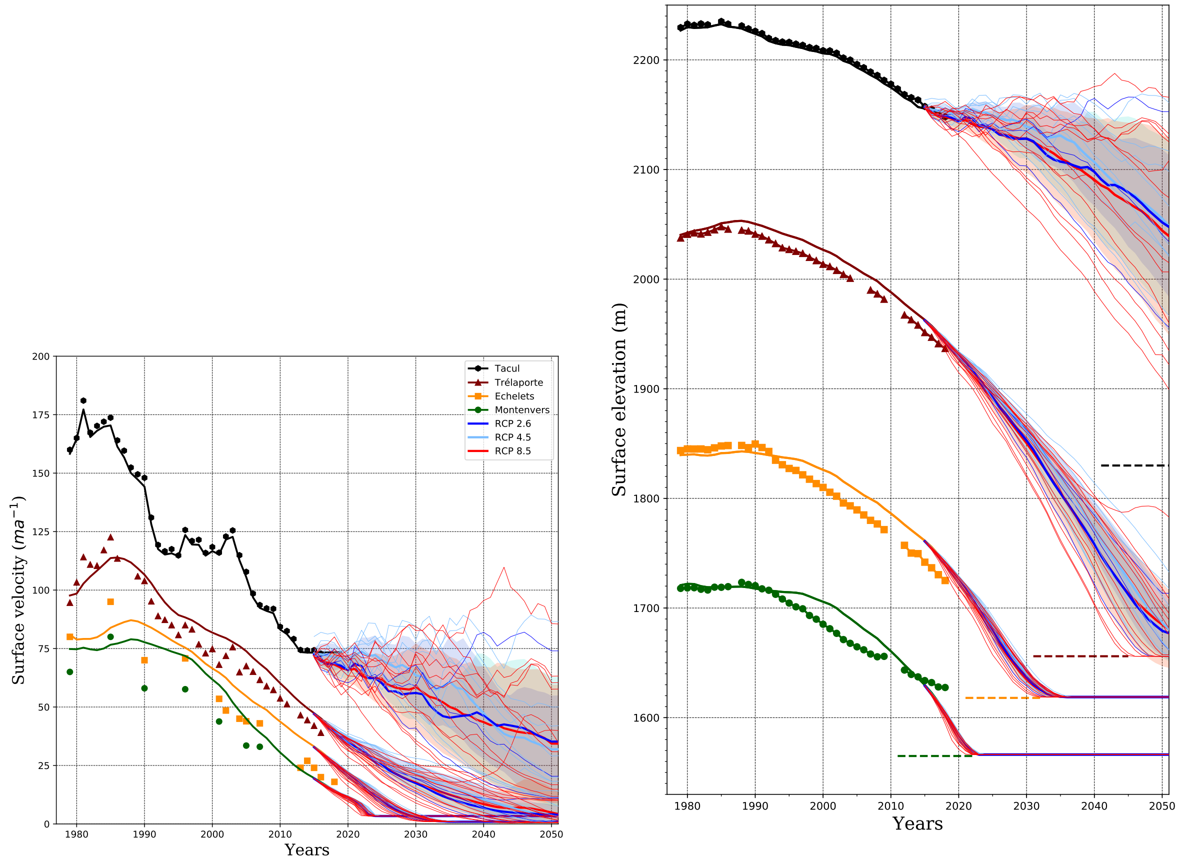

Figure 5. Surface velocity and surface elevation for all prognostic simulations. Hindcasts at the 4 profiles are shown by blark (Tacul), brown (Trélaporte), orange (Echelets) and ?green? (Montenvers) curves and the symbols are the corresponding observations. Forecasts are shown in in dark blue (RCP 2.6),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

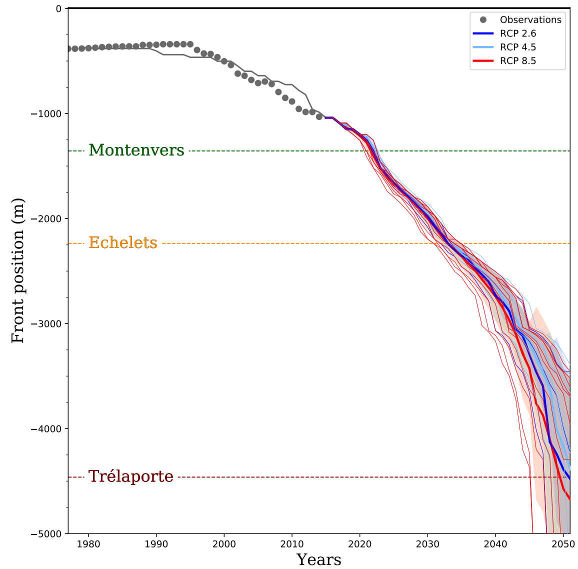

Figure 6. Evolution of the front position (along a flowline defined by the front fluctuation). The hindcast is in grey, and the squares represent observations. Forecasts are shown in dark blue (RCP 2.6), blue (RCP 4.5) and red (RCP 8.5) with 3 extreme scenarios underlined with thick curves and average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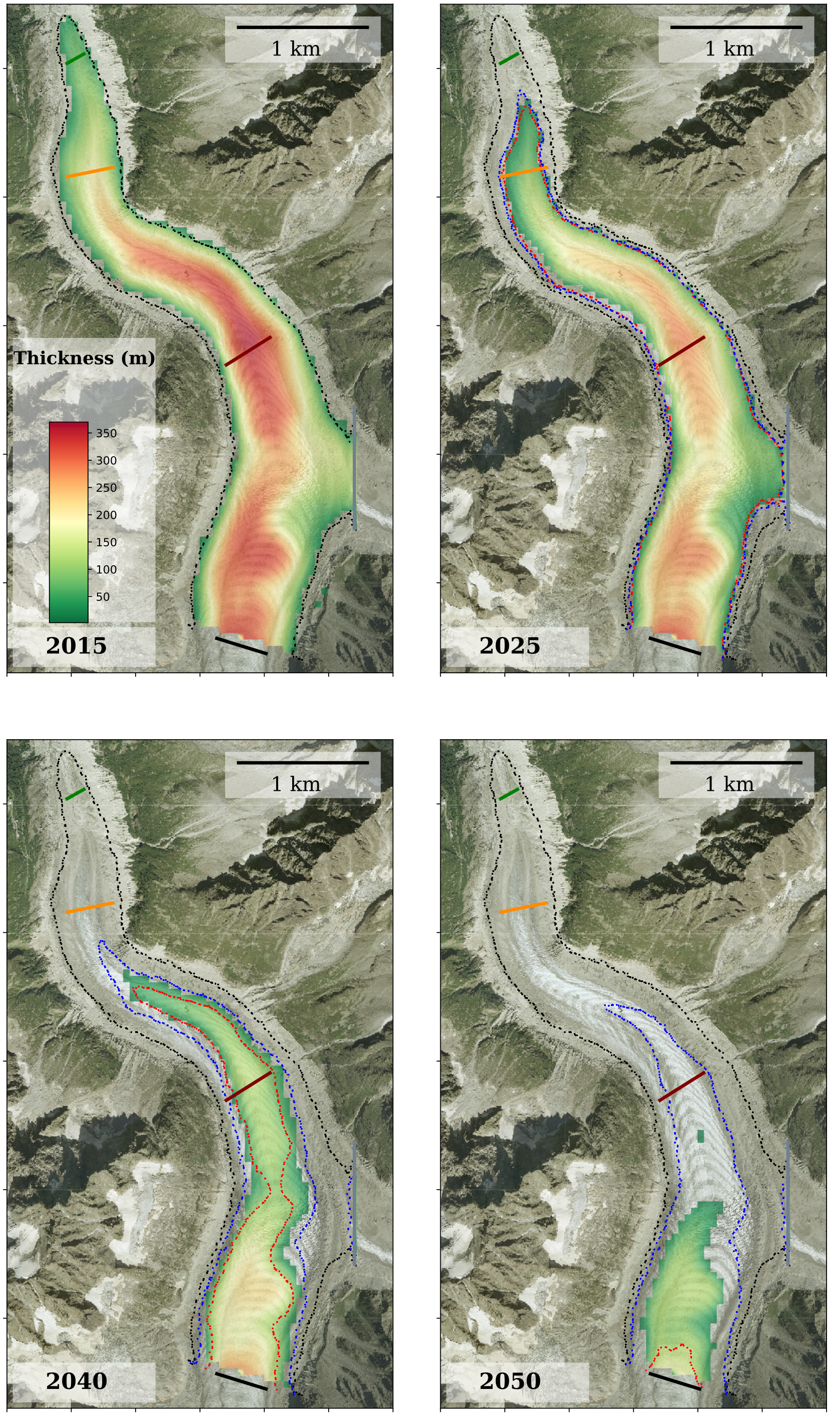

Figure 7. Ice thickness and glacier extension a) at the end of the hindcast simulation in 2015 and for the mean reference forecast simulation in year b) 2025, c) 2040 and d) 2050. The climate scenario for the mean reference forecast simulation is the average of all 26 climate scenarios. Extensions of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

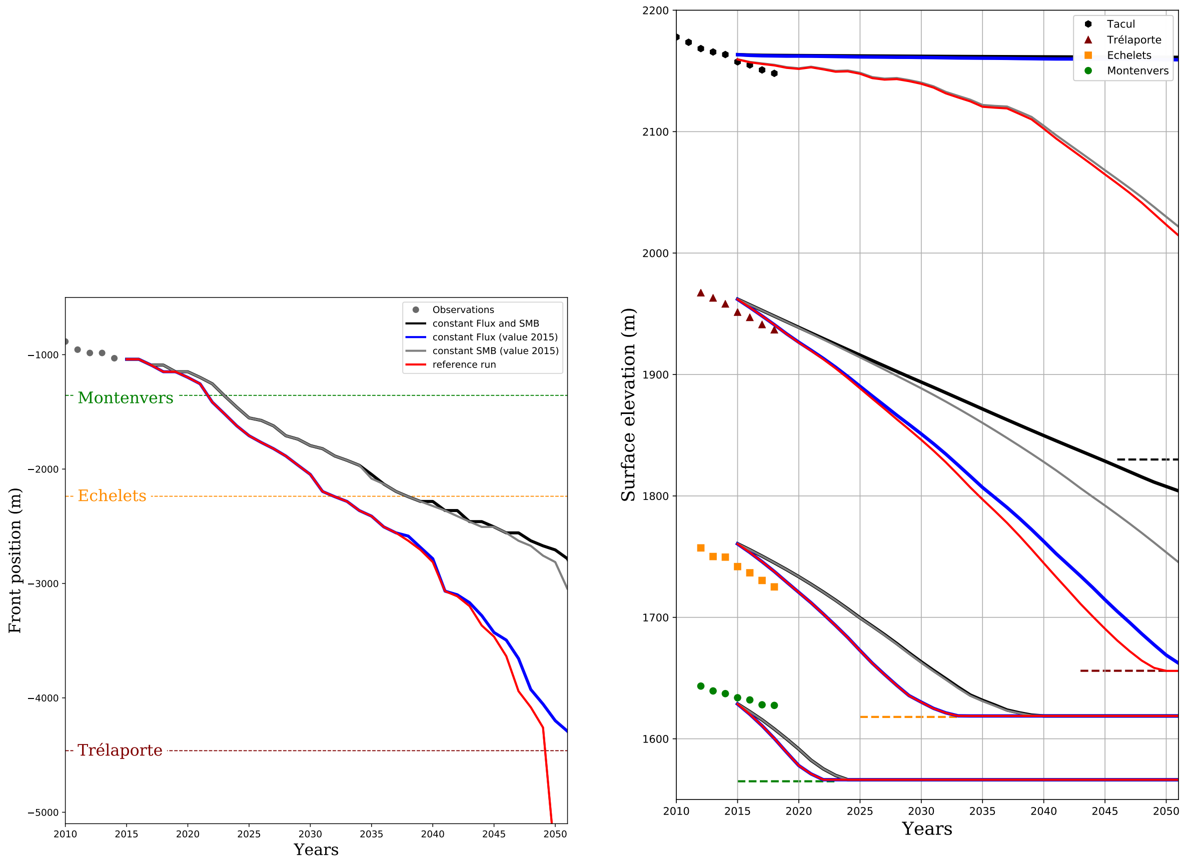

Figure 8. Sensitivity experiment for the mean reference scenario assuming the mean surface mass balance of all scenarios. Evolution of a) the glacier front and b) the surface elevation for this mean reference scenarios (red), assuming a constant surface mass balance (grey, value from year 2015), assuming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

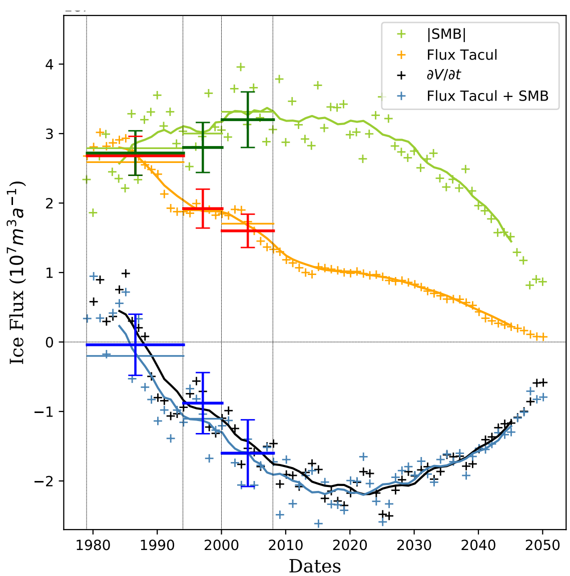

Figure 9. Sensitivity experiment for the mean reference scenario assuming the mean surface mass balance of all scenarios. Evolution with time of the absolute value of the integrated surface mass balance (green, real value always negative), integrated flux at Tacul gate (orange, always positive) and changes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