

Referee #1: Mathieu Morlighem

First, we would like to thank Mathieu Morlighem for his insightful comments on our paper.

General comments

This is a very important topic that has not received a lot of attention so far. The paper is well written and easy to follow. I don't have any major comment but a few suggestions outlined below.

First, three friction laws are used:

- Linear Weertman ($m = 1$)
- Nonlinear Weertman ($m = 1/3$)
- Nonlinear Budd ($m = 1/3$)
- Nonlinear Schoof ($m = 1/3$ and $C_{max} = 0.4$)
- Nonlinear Schoof ($m = 1/3$ and $C_{max} = 0.6$)

I understand that the authors cannot run every possible combination, but it would be great if they could include the friction laws that are commonly used in the ice sheet modeling community. The linear Budd law ($m = 1$), for example, is extensively used by multiple groups (ISSM, UW, etc), much more than the nonlinear Budd law. It would be great to see how it compares with respect to other laws. These experiments could also be useful for intercomparison projects such as ISMIP6 in order to better understand the differences in model projections, but this would only be possible if common laws are tested. Also, why is the Budd sliding law only tested with one of the inferred initial states? Is it a problem of computational resources? It feels like the analysis is incomplete.

We acknowledge that the linear Budd law is extensively used in the modelling community as well. Therefore, we have decided to test this law too, but for the inferred state $I_{R\gamma,100}$ only. Indeed, given the size of the domain and the mesh refinement required to capture the main flow features, we had to split the computational domain in 24 partitions and to affect 4 CPUs to each partition so that simulation durations were not too long. As a consequence, running a 100-year pronostic simulation for one particular combination inferred state/friction law/pronostic experiment (i.e. ABMB or CONTROL) costs around 11000 hours CPU. Since the Budd law induces a depence of $|\tau_b|$ on N over the whole ice sheet, even in its interior where a drainage system may not be present, and since it does not imply any upper bound on the value of $|\tau_b|/N$, we consider the Budd law as being the least physically acceptable one among all the tested laws. This is the reason why we have decided that both the linear and non-linear Budd laws would be tested for $I_{R\gamma,100}$ only, which is the most physically acceptable inferred state. Information regarding the computational cost of transient simulations, as well as explanations regarding the reason why the Budd laws are tested for $I_{R\gamma,100}$ only, have been added to the manuscript.

Specific comments

Lots of comma missing before "which" and "where".

Commas have been added before some of the "which" and "where".

- p1 l3: to a schematic perturbation → to a prescribed perturbation
- p1 l11: much higher → significantly higher
- p1 l21: trustworthy → reliable
- p1 l21: modelling of GL dynamics ...
- p1 l22: as close as possible to observations.
- p2 l1: have come up → have been developed
- p2 l7: have shown that, at large strain, the till ...

- p2 113: behaves very similarly → behave similarly
- p2 127: schematic perturbation → prescribed perturbation
- p2 128: consider removing “To reach our goal,”
- p2 133: we apply a synthetic perturbation to the basal melting rate under floating ice, to the different...

We followed your suggestions for all the points listed above.

- p3 Figure 1: label Cosgrove ice shelf on the figure (in green)

Figure 1 has been modified to add the name of all ice shelves (in black).

- p3 eq 1: double check but given your definition of τ_b , the sign in front of $\tau_{b,x}$ and $\tau_{b,y}$ should be +.

You are right, this was a mistake, which has been corrected.

- p3 eq 2: Did you forget to divide the integral by the ice thickness H?

We think that the way $\bar{\eta}$ was defined in the first version of the manuscript was consistent with the way it was used in Eqs. (1) and (13). However, given your comment and the one of Referee #2, we have decided to redefine $\bar{\eta}$ as being the vertically averaged effective viscosity, which now reads $\bar{\eta} = \bar{\eta}_0 D_e^{(1-n)/n}$, with $\bar{\eta}_0 = \frac{1}{H} \int_{z_b}^{z_s} \frac{1}{2} A^{-1/n} dz$. Eqs. (1) and (13) have been corrected accordingly.

- p5 16: I think a_s should be defined as the surface mass balance instead of just the accumulation rate (it may be negative in some places). That’s how it is defined in p6 19
- p6 112: these two pinning points ... to be critical because of the ...
- p6 127: being submitted → undergoing
- p7 118: impurity content
- p7 118: the question is whether

We followed your suggestions for all the points listed above.

- p9 122: initializing the friction based on driving stress was first proposed by Morlighem et al. 2013

The reference has been corrected.

- p10 111: the coefficient of other laws, which ...
- p10 130: all over the model domain
- p11 114: rephrase “are submitted to”, maybe “the 13 initial states are then run for 105 years under two different scenarios: (1) ...”

We followed your recommendations for all the points listed above.

- p13 117 seldom exceeds 10 % → rarely exceeds 10% (no space between before a percentage sign)

This has been corrected and we have also removed all the spaces before percentage signs.

- p13 124 significative → significant
- p13 132: focus on → focuses on
- p14 111: Independently → Irrespective
- p14 116: all over the 105 a → over the entire 105 a
- p15 132: as going further → as we go further

- p17 110: the lower ... the higher
- p17 118: an increase in ice velocities
- p17 123: as going further → as we go further
- p17 132: as Thwaites glacier is mostly unconfined
- p17 135: a MISI likely initiates
- p19 14: The perturbation experiments

We followed your suggestions for all the points listed above.

- p19 116: You have not really shown that a subglacial hydrology model is needed here, maybe rephrase the sentence

The sentence has been modified.

- p17 figure 8: increase the width of the grounding lines

This has been done.

Referee #2: Thomas Kleiner

First, we would like to thank Thomas Kleiner for his insightful comments on our paper.

General comments

Unfortunately, the authors do not conclude about the most appropriate friction law for the ASE study site. In addition to that, the discussion of the results is based on the numerical flow modelling only. Constraints on the friction law based on observational data are entirely ignored, but should be included to gain the scientific outcome of this study. The ASE is probably the area in Antarctica that is covered by observations the most (e.g. Rippin et al., 2011; Smith et al., 2013; Brisbourne et al., 2017). If discussed with respect to observations, the study could already be a significant contribution “on getting a better understanding of the physical processes at play at the ice/bedrock interface in order to constrain the form of the friction law which needs to be used in models.”

The scientific outcome of the present study is to unequivocally show that projections regarding the future dynamical contribution of an ice sheet to SLR are highly sensitive to the chosen friction law, even on timescales as short as 100 years. Using observations to constrain the form of the friction law which is best suited for a given application would surely constitute a huge leap towards producing reliable projections of future SLR, but, as explicitly stated in the introduction, is not the objective in the present study. It is true that several set of observations regarding the conditions beneath part of the ASE - usually limited to Pine Island as in the studies you cited - are available. However, for a given unique set of observations, the inferred basal stress must satisfy the global stress balance, so the solution of the inverse problem leads to the same basal stress whatever the chosen friction law. Constraining the form of the friction law would then require observations at different times with significant differences in basal velocities, basal stresses and water pressure at the ice/bed interface. Unfortunately, these multiple sets of observations are not available or incomplete. In particular, the water pressure at the ice/bed interface is largely unknown and the assumption of perfect hydrological connection to the ocean is too gross for the purpose of constraining the form of the friction law. In addition, although the dependence of basal shear stress to basal roughness is well acknowledged, formulating a mathematical relationship relating parameters regarding the topographical properties of the bed (local roughness, maximal slope of bumps,...) to the basal shear stress is far from being straightforward.

For all these reasons, all the friction laws commonly used in modelling studies are derived from theoretical arguments (e.g Weertman, 1957; Schoof, 2005; Tsai et al., 2015) or from laboratory experiments (e.g Budd et al., 1979; Iverson et al., 1998) but none of them has been validated *in situ*. Since they report the presence of soft sediments beneath Pine Island Glacier, the studies of Smith et al. (2013) and Brisbourne et al. (2017) tend to support, in this region only, the use of a Schoof law, rather than a Weertman or a Budd law, as the former induces a Coulomb friction

regime in the vicinity of the GL, which has been shown from laboratory experiments to be the most adapted friction regime to represent the deformation of sediments (e.g. Iverson et al., 1998). Yet, this is in no way a validation of the Schoof law, and it does not provide any information regarding the spatial distribution which should be adopted for the parameters C_S , C_{max} and n .

These aspects have been briefly discussed in Brondex et al. (2017), and a bit more thoroughly in Gillet-Chaulet et al. (2016). Anyway, we have added a small paragraph within the discussion section to state that, although available observations are not sufficient to constrain the form of the friction law which ought to be used, they tend to support the use of a Schoof law rather than the two other laws.

I have overlooked this several times, but the rheology parameters A_0 and Q , given in Table 1, are very uncommon. Especially the pre-exponential factor A_0 for temperatures above -10°C differs by several magnitudes from the commonly used Paterson and Budd (1982) parameterization of the Arrhenius Law Eq. (4). I have checked Elmer-Ice (Gillet-Chaulet et al., 2012), ISSM source code and PISM source code. They all use very similar values as in EISMINT (Payne et al., 2000). With the reported values in this study, the viscosity would be much larger (see Figure 1) and thus, the friction law more important. Given the specific ice rheology in this study, I have strong doubts, whether the results can be transferred to other models. If these values are not just different (wrong?) in the table, I would highly recommend to re-run the experiments with a more common set of parameters.

The rheology parameters used in our study are calibrated from values recommended by Cuffey and Paterson (2010). For $T < -10^\circ\text{C}$, these authors suggest to use $Q_1 = 60\text{ kJ mol}^{-1}$, which was already the value suggested by Paterson and Budd (1982). For $T > -10^\circ\text{C}$, Cuffey and Paterson (2010) suggest to use $Q_2 = 115\text{ kJ mol}^{-1}$, whereas Paterson and Budd (1982) recommended $Q_2 = 139\text{ kJ mol}^{-1}$. In addition, according to Cuffey and Paterson (2010), the value of the rate factor at $T = -10^\circ\text{C}$ should be $A(-10^\circ\text{C}) = 3.5 \times 10^{-25}\text{ Pa}^{-3}\text{s}^{-1}$ rather than $A(-10^\circ\text{C}) = 4.4 \times 10^{-25}\text{ Pa}^{-3}\text{s}^{-1}$ as recommended by Paterson and Budd (1982). These differences in the values of Q_2 and $A(-10^\circ\text{C})$ explain the difference of several order of magnitudes in the value of the pre-exponential factor $A_0(T > -10^\circ\text{C})$ between the one we used (Table 1 of the manuscript) and the one suggested by Paterson and Budd (1982). Note however that, as it can be seen on Fig. 1 of your review, the rate factor A used in our study and the one deduced from the values of Paterson and Budd (1982) differ at most by a factor of 2 (i.e. when $T \rightarrow 0^\circ\text{C}$), despite the gap in $A_0(T > -10^\circ\text{C})$. Note also that, although the values of Paterson and Budd (1982) were the ones adopted by most of the authors a few years ago (e.g. Payne et al., 2000; Winkelmann et al., 2011; Larour et al., 2012; Gillet-Chaulet et al., 2012), many recent modelling studies, including studies based on ISSM (e.g. Morlighem et al., 2016; Yu et al., 2016; Seroussi et al., 2017) or Elmer/Ice (e.g. Gillet-Chaulet et al., 2016), make use of the new values recommended by Cuffey and Paterson (2010). In addition, in many studies an enhancement factor is included in order to modify the viscosity. In such a case, it makes no sense to compare the rate factors without including the effect of the enhancement factor, which often differs from one study to the other.

For all these reasons, we did not consider running the experiments with other rheology parameters. We have simply added the reference to Cuffey and Paterson (2010).

Specific comments

- P. 1, L. 3: “Amundsen Sea Embayment” → “Amundsen Sea Embayment”
- P. 1, L. 16: “to the oceans” → “to the ocean”
- P. 1, L. 21: “trustworthy” consider “accurate/reliable”
- P. 1, L. 22: “subcentennial timescales” → “sub-centennial timescales”
- P. 1, L. 25: “a long standing problem” → “a long-standing problem”
- P. 2, L. 19: “geometry and velocity field” → “geometry and (the) surface velocity field”
- P. 2, L. 23: “Yet, Adhalgeirsdottir et al. (2014) have shown . . . ”
- P. 2, L. 24: Consider “initial state of the model” instead of “model initial state”

We followed your suggestions for all the points listed above.

- “Our work being based on a schematic perturbation scenario, the results . . . of the ASE to SLR.” This sentence appears to be incomplete.

We think that this sentence is actually complete.

- P. 3, L. 1?: “two-dimensionnal” → “two-dimensional”

It has been corrected.

- P. 3, L. 1?: Consider “shelfy-stream approximation (SSA)” instead of or in addition to “shallow shelf approximation (SSA)” here, because of the basal shear stresses. This is widely used in the literature for MacAyeal’s equations (e.g. in Morlighem et al., 2010).

We followed your recommendation.

- Although formal correct I would recommend to rewrite Eq. 1 with $\bar{\eta}$ as the vertically averaged effective viscosity with units Pa s (instead of integrated units: Pa s m). Thus, ...

We followed your recommendation.

- P. 4, L. 1: “... η_0 is the viscosity given by ...” It is very misleading to call η_0 a viscosity, because it is obviously not (see units, e.g. in your Fig. 4). The equations (2) and (3) are correct and also how they are applied is correct, but your η_0 is only a substitution for the temperature dependent contribution to the viscosity, thus

$$XXX = \frac{1}{2}A^{-1/n} = \frac{1}{2}B, \quad (1)$$

where A is the rate factor depending on the temperature relative to the temperature melting point and B is the associated rate factor (Greve and Blatter, 2009, p. 56). I am specifically asking for a better name and symbol for XXX.

It is true that η_0 is not, properly speaking, a viscosity. However, since adjusting this quantity is an indirect way to adjust effective viscosity itself, we think it will be clearer for the reader if we keep the notation as it was in the previous version of the manuscript. Therefore, we have simply replaced η_0 by $\bar{\eta}_0$, as well as $\eta_{0,ref}$ by $\bar{\eta}_{0,ref}$, in order to stress that these quantities are vertical averages. In addition, we have modified the manuscript so that these quantities are no more referred to as “viscosities” in the text.

- P. 4, L. 3: Although A is called “fluidity parameter” already in Brondex et al. (2017) consider to use the commonly used term “rate factor” instead (Gillet-Chaulet et al., 2012; Gagliardini et al., 2013). Consider to use T' instead of T to account for the different meaning. Please state clearly, if you have used the temperature or the pressure corrected temperature from Van Liefferinge and Pattyn (2013).

We have changed “fluidity parameter” for “rate factor” as suggested. We have also changed T for T' and explicited the fact that T' is the temperature relative to the pressure-melting point.

- P. 4, Eqns. (5-7): The “-” signs in front of $\tau_{b,x}$ and $\tau_{b,y}$ appear to be wrong in Eq. (1) with this notation of the different friction laws. Consider to use $\tau_b = \dots$ as in Brondex et al. (2017, Eqns. (1-3)).

The “-” signs in Eq. (1) were indeed wrong and have been corrected. We decided to keep the form of Eqs (5-7) as in the previous version of the manuscript, as we want to stress the fact that, in the present study, $\boldsymbol{\tau}_b$ and \mathbf{u}_b are vectors, which are aligned and with opposite directions. In Brondex et al. (2017), the geometry was unidimensional and we could directly write $\tau_b = \dots$

- P. 5, L. 6: “where a_s is the meteoric accumulation rate applied to the top surface of the whole domain and a_b ...” Use “surface mass balance” for a_s as on page 6 line 9. I would suggest something like “where a_s is the surface mass balance a_b applied to the top surface of the whole domain ...”. It should be stated that basal melt is ignored for the grounded part of the ice and why in another sentence.

We have changed “meteoric accumulation rate” for “surface mass balance”. We have also added “Basal melt at the ice/bed interface is neglected.”

- P. 5, Eq. (13): “ $\bar{\eta}$ ” → “ $H\bar{\eta}$ ” with $\bar{\eta}$ being the average effective viscosity. See also P. 4, L. 1 above.

This has been changed.

- P. 5, L. 25: Although this can be guessed from the figures, it should be stated that the calving front is not evolving.

This information has been added.

- P. 6, L. 30-33: Why is the Budd law only applied to one of the inferred states?

See the answer to the general comments of Referee #1.

- P. 6, L. 33: “one of the inferred state” → “one of the inferred states”?

This has been corrected.

- P. 7, Table 1: The numbers for the pre-exponential factors A_0 and activation energies Q for ‘warm’ and ‘cold’ ice are very unexpected. See the Major concerns and suggestions section.

See the answer in the previous part.

- P. 7, L. 6: “ice temperature map” I am not sure what this means. The word map suggests something two-dimensional for me, but the temperature is used for the rate factor A and thus η_0 within the integral of Eq. (2). May “three-dimensional temperature field/distribution” fits better. If the temperature is a three-dimensional field, than it is not clear what is shown as map in your figure 4g.

You are right, it is actually a 3D temperature field, which is used to derive a 3D field of A based on Eq. (4), which is then vertically averaged to get $\bar{\eta}_{0,ref}$ based on Eq. (3). It is this vertical average that is shown in Fig. 4g. This has been made clearer in the manuscript.

- P. 7, L. 7: “a reference viscosity field” and rename $\eta_{0,ref}$ as mentioned above (P. 4, L. 1).

This has been done. See the answer above.

- P. 7, L. 6: The temperature field from Van Liefferinge and Pattyn (2013), based on the model of Pattyn (2010) is a very important part for this study. Therefore, the methods used to get this field should be summarised within a few sentences. Which data set is applied here (ensemble mean, one specific ensemble member)?

In the present study we are using a number of datasets which are all equally important to construct our model initial states. All these datasets are correctly referenced and the interested reader is free to read the corresponding articles if needed, including the paper of Van Liefferinge and Pattyn (2013). The temperature field that we have been using for the present study was actually provided by Van Liefferinge (personal communication), who made a specific run for this purpose as ice shelves were not included in the original work of Van Liefferinge and Pattyn (2013). This is now explicitly stated in the text.

- P. 7, L. 8: “on each nodes of a regular grid”
- P. 7, L. 18: “wether” → “whether”

These two mistakes have been corrected

- P. 8, L. 2-4: “Indeed, several model states ... adjusting rather the basal shear stress or rather the viscosity.”

We have decided to leave this sentence as it was because we want to stress the fact that both the basal shear stress field and the viscosity field are adjusted at the same time, but with various relative weight.

- P. 8, L. 5: “we construct three inferred states - denoted I_{SV} , $I_{R\gamma,100}$ and $I_{R\gamma,1}$ - by means of the control method” At this place the inferred states are introduced by names and the reader needs to continue reading until page 9, line 17 for the explanation of $I_{R\gamma,100}$ and $I_{R\gamma,1}$. This might be unavoidable as a number of equations must be presented first. Nevertheless, I missed the explanation of the subscript ‘SV’ in I_{SV} until the end of the document.

It is true that the reason why we use the notations $R\gamma,100$ and $R\gamma,1$ becomes obvious only from Eq. (19) or even a bit further. However, as you said, we have no choice as a number of equations must be presented first. It is also true that the subscribe SV does not necessarily make sense in english and we have decided to change it for $R\gamma,\infty$

- P. 9, L. 3-4: Consider to move “respectively” further to the end of the sentence: “... which are related to the linear Weertman law coefficient and the viscosity, respectively, as follows:”, but this is personal preference only.

We followed your suggestion.

- P. 9, L. 32: “occurence” → “occurrence”

This has been corrected.

- P. 10, L. 21-22: “except for the Budd law for which the identification has been done only for the case $I_{R\gamma,100}$ ” Why?

See the answer to the general comments of Referee #1.

- P. 10, L. 23: “at every grounded nodes covered with ice”
- P. 10, L. 24: “which are ice free” → “which are ice-free”
- P. 11, L. 5: “which are ice free” → “which are ice-free”
- P. 12, L. 11: “local adjustement of viscosity”
- P. 12, L. 18: “the inversion algorithm#”
- P. 12, L. 23: “has already been showed” → “has already been shown”

All these points have been corrected.

- P. 12, L. 21-25: “It is also this same mechanism ... Borstad et al., 2012, 2013).” Although damage could play a role, I am not convinced of this argument. I think, the shear margins are just not well enough resolved in the velocity field that has been simulated in the study by Van Liefferinge and Pattyn (2013, 5 km horizontal resolution). Unfortunately, ice flow velocities are not presented in Van Liefferinge and Pattyn (2013) or Pattyn (2010). The basal drag in an ice stream is usually low, thus the lateral drag at the shear margins balances the ice stream’s driving stress. Similar to the condition at an ice sheets base, the drag leads to deformation of ice (strain) and thus strain heating. As the viscosity depends on temperature the viscosity decreases (see e.g. Bondzio et al., 2017). This is supported by your figure 4 panel g, where no viscosity variations across the shear margins of PIG near the GL are visible. The cited literature is only related to ‘damage’ in ice shelves (Larsen B and C) and not appropriate for the conditions in the ASE.

The low viscosity bands to which we refer are located on Pine Island and Thwaites ice shelves and not within the grounded part of the ice streams (see Fig. 4h), therefore we think that the cited literature is totally relevant in this case. We agree that lateral drag at the shear margins must balance the driving stress as ice shelves do not experiment any basal drag. Beside strain heating which you are mentioning, it also causes locally high shear stresses leading to opening of fractures which makes ice softer. Indeed, several authors have reported the good correlation between these low viscosity bands and aerial observations of crevasses (e.g Borstad et al., 2013). Another mechanism which also tends to decrease ice viscosity at shear margins is the development of crystalline fabric which induces anisotropy in ice rheology, making ice softer in some stress directions and stiffer in others (Minchew et al., 2018). Saying whether the low viscosity bands are due to strain heating, anisotropy, damage, or to a combination of the three, is difficult. Therefore, we have added to the manuscript the fact that strain heating and anisotropy could also be potential explanations for the presence of these soft bands.

- P. 13, L. 1: “loosing” → “losing”
- P. 13, L. 10: “at every grounded nodes”
- P. 13, L. 19: “whithin” → “within”
- P. 13, L. 31: “the relative differences on in the velocity field”?
- P. 14, L. 1: “the gaussian integration” → “the Gaussian integration”

- P. 15, L. 19: “is primary controlled by” → “is primarily controlled by”
- P. 15, L. 23: “significantly different than the” → “significantly different from the” My preference.

We followed your suggestions for all the points listed above.

- P. 15, L. 23: “ $z_f = \dots$, constitutes the thickness above flotation.” This is only true for grounded ice. Consider to show the flotation altitude (red line in Fig. 9) only for the grounded part.

We have made this point clearer in the text as well as in the caption of Fig. 9. However, we chose not to change the latter as different “grounded parts” are actually represented in each plot, i.e. two for the Budd law, two for the Schoof law and the initial profile which is common to the two laws.

- P. 16, L. 7: “Dotson ice shelve” → “Dotson Ice Shelf”
- P. 16, L. 8: “viscosiy” → “viscosity”
- P. 16, L. 11: “tens of degrees celsius” → “tens of degrees Celsius”

We have corrected these points.

- P. 16, L. 12: “temperature map” See comment above (P. 7, L. 6).

The word “map” has been replaced by “field”

- P. 17, L. 2: “showing a highest contribution” → “showing the highest contribution”
- P. 17, L. 28: “leading to important retreat of the GL” → “leading to an/the important retreat of the GL”
- P. 17, L. 30: “occurence” → “occurrence”
- P. 17, L. 33: “solid black line in bottom left panel of Fig. 9” → “solid black line in the bottom left panel of Fig. 9”
- P. 18, L. 23: “parameters are uncertain” → “parameters are uncertain”
- P. 18, L. 24: “viscosity is not inferred but ~~simply~~ deduced”

We followed your suggestions for all the points listed above.

- P. 18, L. 24: “ice temperature maps” See above.

The word “maps” has been replaced by “fields”

- P. 18, L. 31: “equals to the value of” or “is equal to the value of”
- P. 19, L. 1-2: Consider to rearrange the sentence (personal preference only). E.g. “This procedure induces significant but very localised discrepancies between the recomputed velocity field and the reference velocity field used for the identification, in particular within ice shelves.” or “... particularly within ice shelves.”

We followed your suggestions for the two points listed above.

- P. 19, L. 4-16: The authors state very clear at the beginning (P. 2, L. 28), that “... the results presented here should not be considered as actual projections of the future contribution of the ASE to SLR.” Consider to choose other terms to replace “projections” within this and other parts of the text.

Although we do not make actual projections of the future contribution of the ASE to SLR in the present study, the latter shows sensivity of mass loss projections to the friction law and initialisation strategy. In this sense, the use of the word “projection” appears correct to us in most of the text. Yet, we agree that this term was improperly used in one of the sentences of the conclusion section. This has been corrected.

- P. 19, L. 14: “constain” → “constrain”

This has been corrected.

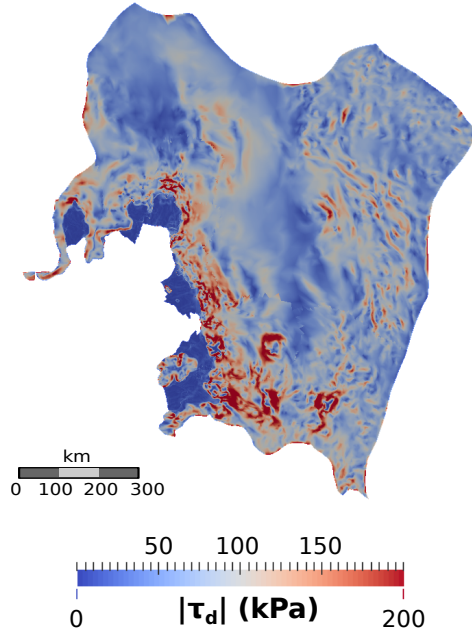


Figure 1: $|\tau_d|$ (kPa) after initialisation.

- P. 24, Fig. 4: I think, maps of the basal shear stress $|\tau_b|$ are required in addition to the stress ratios presented in (d,e,f) for the three inferred states. This would allow to compare your inversion with other modelling studies conducted in this area (e.g. Joughin et al., 2009; Morlighem et al., 2010) and observational data. A large portion of your model domain appears white in the panels a-c indicating that observed velocities are not available here. This is not so easy to see in Rignot et al. (2011), but in Mouginot et al. (2014, Fig. 1). Please explain how do you conduct the inversion in these areas. It is not clear, how the features in the panels d-f can be explained, given the extensive data gap in a-c.

It is true that comparing the inferred fields of $|\tau_b|$ to Figs. 5-6 of Joughin et al. (2009), or to Fig. 2 of Morlighem et al. (2010), can be interesting, although colorscales are different. On the other hand, we don't think that adding maps of $|\tau_b|$ to Fig. 4 of the manuscript, which is already a heavy figure containing a lot of information, would be relevant in the context of the paper. Therefore, we have decided to add these maps of $|\tau_b|$ in a supplementary material.

As stated in the text of the manuscript, the cost function J_v quantifying the misfit between modelled and observed velocities is evaluated at observation points. You are right when saying that there is a large region which is not covered by observation points. As a consequence, the solutions obtained in this region for the fields of α and γ stay close to the initial guesses (i.e. α such that $|\tau_b| = |\tau_d|$ and γ such that $\bar{\eta}_0 = \bar{\eta}_{0,ref}$), except that they are smoother because of the regularisation functions $J_{reg,\alpha}$ and $J_{reg,\gamma}$, which are evaluated over the whole domain. However, the lack of information in this region is not critical as the flow of ice is known to be very slow over there. We have represented, in Fig. 1 of the present document, the norm of the driving stress $|\tau_d|$ which is calculated from the gradient of the surface elevation z_s as follows:

$$\tau_d = \rho_i g H \text{grad}(z_s). \quad (2)$$

Comparing this figure to Fig. S1 of the supplementary material shows that the fields of $|\tau_b|$ obtained in the region where surface velocities are missing look like smoothen versions of $|\tau_d|$. Therefore, the "wave-like" features of $|\tau_b|/|\tau_d|$ observed on Fig. 4d-f of the manuscript in this region come from similar features in $|\tau_d|$, which are not present in $|\tau_b|$. These features in $|\tau_d|$ are likely due to the irregularity of $|\text{grad}(z_s)|$ in this region, as it can be seen in Fig. 2 of the present document.

- P. 25, Fig. 5: I can't see any difference between a,b and c. The tiny little areas in between the green and grey areas appear all just red. The zoom in area should be marked in one of the figures for the whole ASE.

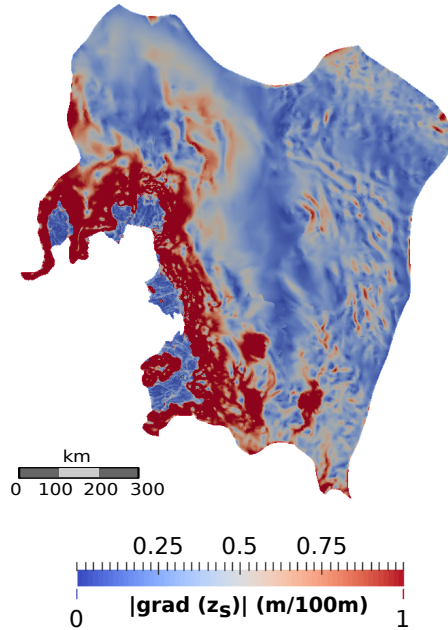


Figure 2: $|\text{grad}(z_s)|$ (m/100m) after initialisation.

The first purpose of Fig. 5a-c is to show that the nodes at which $|\tau_b|$ recalculated with the Schoof law (with $C_{max} = 0.4$) following the identification of C_S differs significantly from the $|\hat{\tau}_b|$ calculated with the linear Weertman law and used for the identification step, are very few (i.e. 8% at most). The second purpose of this figure is to show that these nodes are mostly located close to the ice shelves where ice is almost at floatation, except for some regions located far inland (bottom right corner of Fig. 5a-c) where N is low because of locally very low ice thicknesses, as shown in Fig. 3 of the present document. We think that this two goals are fulfilled with the version of Fig. 5 as it was in the first version of the manuscript. It is true that differences between a,b and c are difficult to distinguish (also because these differences are actually slight), but the reader can still see some small differences between panels (e.g. west part of Thwaites Ice Shelf or upper part of PIG Ice Shelf). We could have focused on a particular region to have a better zoom in, e.g. around Thwaites Ice Shelf, but this would have been to the detriment of other regions of interest, which would have hampered the first purpose of the figure. The zoom in area of Figs. 5a-c has been added on Fig. 5d

- P. 27, Fig. 8: The coloured lines should be slightly thicker.

This has been done.

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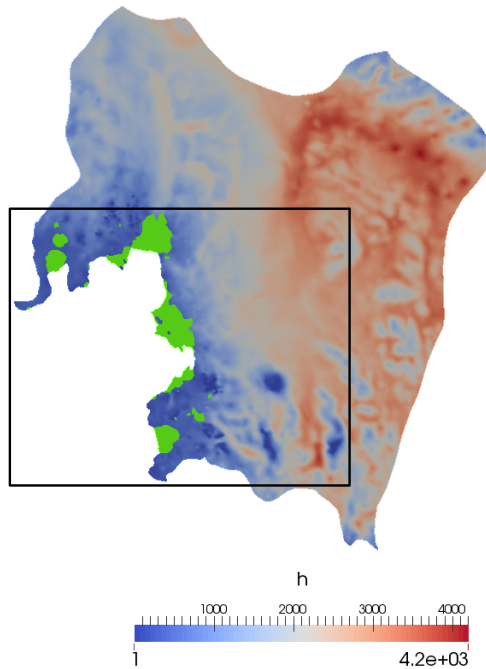


Figure 3: Ice thickness (m) used for initialisation. The black square is the zoom in area of Fig. 5a-c. The ice shelves are in green for consistency with Fig. 5 of the manuscript.

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Sensitivity of centennial mass loss projections of the Amundsen basin to the friction law

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Abstract. Reliable projections of ice sheets future contribution to sea level rise require models able to accurately simulate grounding line dynamics, starting from initial states consistent with observations. Here, we simulate the centennial evolution of the Amundsen Sea ~~Embayement~~Embayment in response to a ~~schematic-prescribed~~ perturbation in order to assess the sensitivity of mass loss projections to the chosen friction law, depending on the initialisation strategy. To this end, three different model states are constructed by inferring both the initial basal shear stress and viscosity fields with various relative weights. Then, starting from each of these model states, prognostic simulations are carried out using a Weertman, a Schoof and a Budd friction law, with different parameter values. ~~Independently of the considered model state, the Weertman law systematically predicts the lowest mass losses.~~ Although the sensitivity of projections to the chosen friction law tends to decrease when more weight is put on viscosity during initialisation, it remains significant for the most physically acceptable of the constructed model states. Independently of the considered model state, the Weertman law systematically predicts the lowest mass losses. In addition, because of its particular dependence on effective pressure, the Budd friction law induces significantly different GL retreat patterns than the other laws and predicts ~~much~~significantly higher mass losses.

1 Introduction

The West Antarctic Ice Sheet mean annual contribution to global sea level rise (SLR) has tripled over the last 25 years as a consequence of a growing imbalance between the mass it receives as snowfall and that which is discharged to the ~~oceans~~ocean by ice streams (Shepherd et al., 2018). The most active basin of this region is the Amundsen Sea Embayment (ASE), where marine-terminating outlet glaciers draining ice to the oceans have shown sustained acceleration and thinning over the last decades, with their grounding lines (GL), i.e. the limit between the grounded ice-sheet and the floating ice shelf, retreating at rates higher than 1 km a^{-1} since 1992 (Mouginot et al., 2014; Rignot et al., 2014). These observations raise concern regarding the near future of the ASE as they suggest that this sector of West Antarctica is undergoing a marine ice-sheet instability (MISI), which would imply a significant additional global SLR in the coming decades (Joughin et al., 2014; Favier et al., 2014; Cornford et al., 2015). Producing ~~trustworthy-reliable~~ estimates of this future contribution requires accurate modelling of the GL dynamics on ~~subcentennial~~sub-centennial timescales as well as the ability to produce model states as close as possible to the observations.

25 Using a synthetic flowline geometry, Brondex et al. (2017) have shown that the GL dynamics depends critically on the choice of the friction law, i.e. the mathematical relationship linking basal shear stress to other parameters including sliding velocity. The ice/bed interface being usually out of reach, the formulation of a friction law has been a ~~long-standing~~long-standing problem in glaciology. Various laws intended to describe different physical processes at the roots of basal motion have ~~come up~~been developed over the years (Weertman, 1957; Budd et al., 1979; Schoof, 2005; Tsai et al., 2015). Most ice flow modelling
5 studies published so far use the Weertman friction law, which aims at describing the basal motion of ice over and around obstacles of a rigid bedrock by a combination of viscous creep and regelation (Weertman, 1957). However, many rapid ice streams of Antarctica are known to be lying on soft beds made of water-laden till, the deformation of which explains most of the motion observed at the surface (Blankenship et al., 1986; Alley et al., 1986; Kavanaugh and Clarke, 2006). Numerous laboratory studies on till samples and in situ measurements have shown that, at large strain, the till rheology is plastic with a
10 critical strength τ^* depending on effective pressure N , i.e. the difference between ice overburden pressure and water pressure (Boulton and Jones, 1979; Blankenship et al., 1986; Alley et al., 1986). To account for both the cases of rigid and soft beds, Tsai et al. (2015) proposed a law inducing a Coulomb friction regime at low N , which instantaneously switches to a Weertman friction regime at higher N . By construction, this law induces an upper bound, function of N , of the basal shear stress. Although it was originally intended to describe the ice flowing over a rigid bed with the opening of water-filled cavities, the law proposed
15 by Schoof (2005) behaves ~~very~~ similarly, except that the transition between the Coulomb and Weertman regimes is continuous, which makes it easier to handle numerically (Brondex et al., 2017).

Although a growing number of information about the current state of the ice-sheet (e.g. surface velocities, surface elevation, surface elevation rates of change) are made available by the rapid development of satellite observations, several model parameters remain poorly constrained (e.g. bedrock elevation, ice viscosity, friction law coefficients). Gradient-based optimisation
20 methods are routinely used to estimate uncertain model parameter fields and boundary conditions so that the initial ice-sheet geometry and surface velocity field are as close as possible to observations (e.g. Morlighem et al., 2010, 2013; Gillet-Chaulet et al., 2012; Cornford et al., 2015). Although such methods enable to deduce the current basal shear stress field from observed surface velocities, the form of the friction law cannot be discriminated with a unique set of observations (Joughin et al., 2004; Gillet-Chaulet et al., 2016). Furthermore, when several uncertain fields are simultaneously inferred, several different initial
25 states consistent with observations can potentially be constructed. ~~Yet,~~ Adhaugeirsdóttir et al. (2014) have shown that SLR projections on decadal timescales are sensitive to the ~~model initial state~~ initial state of the model, which can account for an important source of uncertainty in the model response.

In the present study, we aim at assessing the relative sensitivity of centennial mass loss projections of the ASE to the chosen friction law and initialisation strategy. Our work being based on a ~~schematic-prescribed~~ perturbation scenario, the results
30 presented here should not be considered as actual projections of the future contribution of the ASE to SLR. ~~To reach our goal,~~ The first step consists in building three different model states of the ASE by inferring simultaneously the basal shear stress and the ice viscosity, with various relative weights attributed to each one of these two fields during the inversion. Then, for each of these states, we follow the same procedure as in Brondex et al. (2017) to identify the distributions of the friction coefficients of three commonly used friction laws that lead to the same model initial states. Finally, we apply a synthetic perturbation ~~of~~

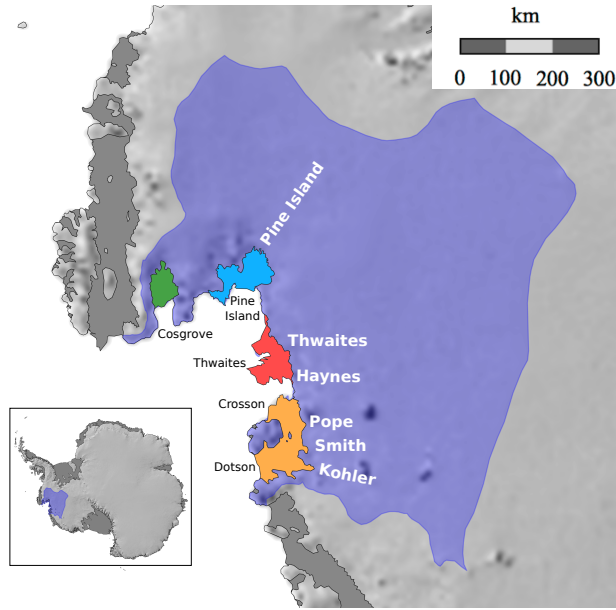


Figure 1. Amundsen Sea Embayment (ASE) and its ice shelves: Cosgrove (green), Pine Island (blue, fed by the Pine Island Glacier), Thwaites (red, fed by the Thwaites and Haynes ice streams), Crosson and Dotson (yellow, fed by the Pope, Smith and Kohler ice streams). The localisation of the ASE is reported on the map of Antarctica in the bottom left corner (purple).

to the basal melting rate under floating ice, to the different initial states and compare the dynamical responses obtained with the various friction laws. In Sect. 2, we give a precise description of the model used to conduct this study and describe the experimental setup. The results obtained at each step of the experiments are presented in Sect. 3 and discussed in the last

5 section.

2 Methods

2.1 Model description

The modeled domain is represented in Fig. 1. For the stress balance, we solve the [two-dimensional shallow shelf approximation](#) [two-dimensional Shelfy-Stream Approximation](#) (SSA) equations (MacAyeal, 1989), for which the horizontal velocity field $\mathbf{u} = (u, v)$ is a solution of

$$\begin{aligned}
 & 4 \frac{\partial}{\partial x} \left(\underline{H} \bar{\eta} \frac{\partial u}{\partial x} \right) + 2 \frac{\partial}{\partial x} \left(\underline{H} \bar{\eta} \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial y} \left(\underline{H} \bar{\eta} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right) \\
 & \qquad \qquad \qquad \underline{\pm} \tau_{b,x} = \rho_i g H \frac{\partial z_s}{\partial x} \\
 5 \quad & 4 \frac{\partial}{\partial y} \left(\underline{H} \bar{\eta} \frac{\partial v}{\partial y} \right) + 2 \frac{\partial}{\partial y} \left(\underline{H} \bar{\eta} \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial x} \left(\underline{H} \bar{\eta} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right) \\
 & \qquad \qquad \qquad \underline{\pm} \tau_{b,y} = \rho_i g H \frac{\partial z_s}{\partial y},
 \end{aligned} \tag{1}$$

where ρ_i is the ice density, g the gravity norm and $H = z_s - z_b$ the ice thickness, with z_s and z_b the top and bottom surface elevations, respectively. The vertically [integrated-averaged](#) effective viscosity $\bar{\eta}$ reads:

$$\bar{\eta} = \int_{\underline{z_b}}^{\underline{z_s}} \eta \bar{\eta}_0 D_e^{(1-n)/n} \underline{dz}, \tag{2}$$

where D_e is the second invariant of the strain-rate tensor, n is the Glen's law exponent and [\$\eta_0\$ is the viscosity- \$\bar{\eta}_0\$ is](#) given by:

$$10 \quad \underline{\eta \bar{\eta}_0} = \frac{1}{\underline{H}} \int_{\underline{z_b}}^{\underline{z_s}} \frac{1}{2} A^{-1/n} \underline{dz}. \tag{3}$$

In Eq. (3), A is the [fluidity parameter rate factor](#). It is related to the temperature [\$T\$ relative to the pressure-melting point \$T'\$](#) ($^{\circ}\text{C}$) through an Arrhenius Law:

$$A = A_0 e^{\underline{\left(-Q/[R(273.15+T)] \right)} \underline{\left(-Q/[R(273.15+T')] \right)}}, \tag{4}$$

where A_0 is the pre-exponential factor, Q is an activation energy and R is the gas constant ([Cuffey and Paterson, 2010](#)).

15 For the basal shear stress τ_b in Eq. (1), we consider three different friction laws:

$$\tau_b + C_W |\mathbf{u}_b|^{m-1} \mathbf{u}_b = 0, \tag{5}$$

$$\tau_b + C_B N |\mathbf{u}_b|^{m-1} \mathbf{u}_b = 0, \tag{6}$$

$$20 \quad \tau_b + \frac{C_S |\mathbf{u}_b|^{m-1} \mathbf{u}_b}{\left(1 + \left(\frac{C_S}{C_{max} N}\right)^{1/m} |\mathbf{u}_b|\right)^m} = 0, \quad (7)$$

where C_W , C_B and C_S are friction parameters. Equation (5) corresponds to the widely used Weertman law (Weertman, 1957), where m is a positive exponent, often related to the creep exponent n of the Glen's law as $m = 1/n$. Equations (6) and (7) correspond to the Budd and Schoof friction laws, respectively (Budd et al., 1979; Schoof, 2005). Note that, on the contrary to the two other laws, the Schoof law induces an upper bound of the ratio $|\tau_b|/N$ known as Iken's bound and equal to the value of the parameter C_{max} (Iken, 1981; Schoof, 2005; Gagliardini et al., 2007). Although it is not its original purpose, the use of a Schoof law - which can be seen as the ~~asymptotical~~-equivalent of the Tsai law (Brondex et al., 2017) - is more and more justified by its ability to represent the deformation of till, as it induces a Coulomb friction regime at low N . In that case, the parameter C_{max} ought to be seen as a Coulomb friction parameter related to the rheological properties of the till. Laboratory measurements have shown that the values of C_{max} should then range between 0.17 and 0.84 (Cuffey and Paterson, 2010).

5 Both the Budd and Schoof laws make an explicit use of the effective pressure N . Using an effective pressure-dependent friction law when running transient simulations proves necessary in order to account for the enhancement of basal sliding due to the presence of subglacial drainage systems connected to the ocean, which have been reported in several studies (Gray et al., 2005; Fricker et al., 2007; Le Brocq et al., 2013). However, unlike the Schoof law for which the dependence of $|\tau_b|$ on N is limited to the close vicinity of the GL, the Budd law induces a dependence of $|\tau_b|$ on N over the whole grounded part of the domain, even far in its interior where such a drainage system may not exist. Ideally, N should be computed by a subglacial hydrology model but the few available models of that kind are usually relying on a multitude of poorly constrained parameters (Schoof, 2010; Hewitt et al., 2012; Werder et al., 2013; De Fleurian et al., 2014) and the attempts to couple these models to ice flow models are relatively recent (Hewitt, 2013; Bougamont et al., 2014; Bueler and van Pelt, 2015; Gagliardini and Werder, 2018). Therefore, in the present study, N is calculated assuming a perfect hydrological connection between the subglacial drainage system and the ocean, so that:

$$N = \begin{cases} \rho_i g H + \rho_w g z_b & \text{if } z_b < 0, \\ \rho_i g H & \text{if } z_b \geq 0, \end{cases} \quad (8)$$

where ρ_w is the water density. A systematic comparison of the dependence of τ_b on N and \mathbf{u}_b implied by these various friction laws is available in Brondex et al. (2017). Note that, since floating ice does not experience any friction, τ_b is set to zero wherever ice is afloat, independently of the chosen friction law.

20 The temporal evolution of ice thickness is governed by a two-dimensional mass transport equation:

$$\frac{\partial H}{\partial t} + \frac{\partial(uH)}{\partial x} + \frac{\partial(vH)}{\partial y} = a_s - a_b, \quad (9)$$

where a_s is the ~~meteoric accumulation rate applied to the top surface of the whole domain~~ surface mass balance and a_b the oceanic melt rate applied to the bottom surface of the ice shelves only, basal melt at the ice/bed interface being neglected. Ice is

assumed to be in hydrostatic equilibrium and the bottom surface elevation can be deduced from the bedrock topography $b(x, y)$ by applying the no-penetration condition and the floating condition. Here we assume a constant sea level $z_{sl} = 0$, so that:

$$\begin{cases} z_b(x, y, t) = b(x, y) & \text{for grounded ice,} \\ z_b(x, y, t) = -H \frac{\rho_i}{\rho_w} > b(x, y) & \text{for floating ice.} \end{cases} \quad (10)$$

The GL being the limit beyond which grounded ice starts floating, its position (x_G, y_G) can directly be deduced from Eq. (10) by solving:

$$H(x_G, y_G) + b(x_G, y_G) \frac{\rho_w}{\rho_i} = 0. \quad (11)$$

Therefore, the GL can be located at any point of the domain and its position is free to evolve over time as a result of evolving geometry.

The positions of the boundaries of the model domain are set based on the observations made by the satellite ICESat for the IMBIE2 effort (Zwally et al., 2012). In the following, $\mathbf{n} = (n_x, n_y)$ is the normal unit vector to the considered boundary. At the ice divides, there is no ice flux entering the domain so that the following Dirichlet condition applies:

$$(\mathbf{u} \cdot \mathbf{n})|_{id} = 0, \quad (12)$$

and is completed by a free slip condition in the tangential direction. At the ice shelves and glaciers fronts, which remain fixed in time, the following Neumann condition applies:

$$\begin{aligned} 4\mathcal{H}\bar{\eta} \left. \frac{\partial u}{\partial x} \right|_f n_x + 2\mathcal{H}\bar{\eta} \left. \frac{\partial v}{\partial y} \right|_f n_x + \mathcal{H}\bar{\eta} \left. \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right|_f n_y \\ = \frac{g}{2} (\rho_i H|_f^2 - \rho_w H_{sub}|_f^2) n_x \\ 2\mathcal{H}\bar{\eta} \left. \frac{\partial u}{\partial x} \right|_f n_y + 4\mathcal{H}\bar{\eta} \left. \frac{\partial v}{\partial y} \right|_f n_y + \mathcal{H}\bar{\eta} \left. \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right|_f n_x \\ = \frac{g}{2} (\rho_i H|_f^2 - \rho_w H_{sub}|_f^2) n_y, \end{aligned} \quad (13)$$

where $H_{sub}|_f$ is the submerged height at the considered front, which is null in the very few places where glacier fronts are grounded and relates to $H|_f$ through the floating condition at floating fronts.

Similarly to Pollard and DeConto (2012), the oceanic melt rate a_b (m a^{-1}), prescribed on the bottom surface of ice shelves **only**, is parameterised as follows:

$$a_b = \frac{8K_T \rho_w c_w}{\rho_i L_f} |T_0 - T_f| (T_0 - T_f), \quad (14)$$

where T_0 and T_f are, respectively, the ocean water temperature and freezing point at the considered depth, K_T is a transfer coefficient for sub-ice oceanic melting, c_w the specific heat of ocean water and L_f the latent heat of fusion of ice. Following Pollard and DeConto (2012), the temperature difference $T_0 - T_f$ is given by: $T_0 - T_f = 0.5^\circ \text{C}$ for $0 > z > -170$ m, 3.5°C for $z < -680$ m and linearly interpolated for z between -680 and -170 m. Values of parameters prescribed in this study are presented in Table 1.

Table 1. List of parameter values used in this study.

Parameters	Values	Units
ρ_i	910	kg m ⁻³
ρ_w	1028	kg m ⁻³
$A_0(T < -10^\circ\text{C})$ $A_0(T' < -10^\circ\text{C})$	2.847×10^{-13}	Pa ⁻³ s ⁻¹
$A_0(T > -10^\circ\text{C})$ $A_0(T' > -10^\circ\text{C})$	2.360×10^{-2}	Pa ⁻³ s ⁻¹
c_w	4.218	kJ kg ⁻¹ K ⁻¹
g	9.81	m s ⁻²
K_T	15.77	m a ⁻¹ K ⁻¹
L_f	335	kJ kg ⁻¹
n	3	
$Q(T < -10^\circ\text{C})$ $Q(T' < -10^\circ\text{C})$	60	kJ mol ⁻¹
$Q(T > -10^\circ\text{C})$ $Q(T' > -10^\circ\text{C})$	115	kJ mol ⁻¹
R	8.314	J mol ⁻¹ K ⁻¹

For the surface mass balance a_s , we use outputs of simulations performed with the MAR model and averaged over the 1979-2015 period (Agosta, personal communication). The bedrock topography is taken from Bedmap2 (Fretwell et al., 2013), except that we include two pinning points in contact with the bottom surface of Thwaites ice shelf using the bathymetry of Millan et al. (2017). The mechanical role of these two pinning ~~point points~~ has indeed been shown to be ~~of first importance~~ critical because of the buttressing effect that they exert on the upstream ice stream (Fürst et al., 2016).

All the equations presented above are solved using the open source finite element code Elmer/Ice (Gagliardini et al., 2013). The mesh is generated using the anisotropic mesh-adaptation technique described in Gillet-Chaulet et al. (2012) so that the distance between two nodes at the GL is of the order of ~ 50 m. Finally, we end up with a mesh made of 274678 nodes covering the whole model domain, the total surface of which is about 4.5×10^5 km². The same mesh is used for all the successive steps of all the experiments presented in the following. In addition, we take advantage of the fact that the GL position is determined at subelement precision through Eq. (11) to make use of the subelement parameterisation SEP3 as proposed by Seroussi et al. (2014). In our case, the number of quadrature points is raised to 20 in the elements containing the GL.

2.2 Experimental setup

In the present study, we aim at comparing the results in terms of GL dynamics and volume losses produced by the following friction laws: (1) a linear Weertman law ~~which corresponds to given by~~ Eq. (5) with $m = 1$, (2) a non-linear Weertman law given by Eq. (5) with $m = 1/3$, (3) a non-linear ~~Budd-Schoof~~ law given by Eq. (67) with $m = 1/3$ ~~and $C_{max} = 0.4$~~ , (4) a non-linear Schoof law given by Eq. (7) with $m = 1/3$ and ~~$C_{max} = 0.4$, and $C_{max} = 0.6$~~ , (5) a linear Budd law given by Eq. (6) with $m = 1$, and (6) a non-linear Schoof-Budd law given by Eq. (76) with $m = 1/3$ and $C_{max} = 0.6$. To reach this goal, we

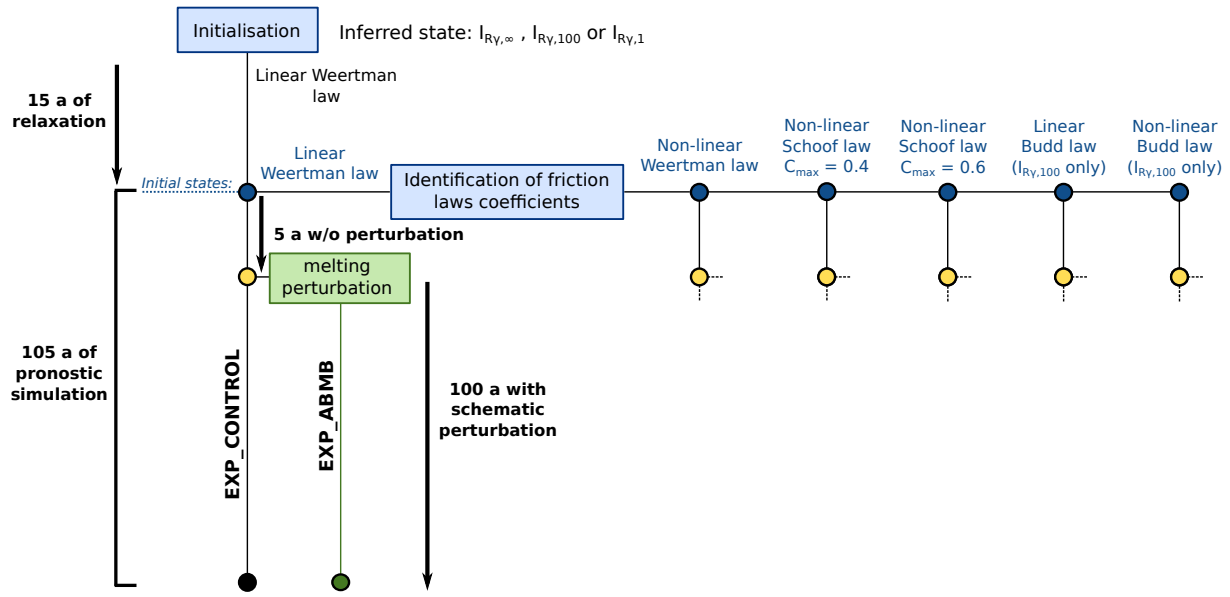


Figure 2. Flowchart summarising the consecutive steps of the present study for a given inferred state. The simulations EXP_CONTROL and EXP_ABMB are run for each of the five friction laws. This-The same procedure is repeated for each of the three inferred states $I_{R_{\gamma,\infty}}$, $I_{R_{\gamma,100}}$ and $I_{R_{\gamma,1}}$, except that the non-linear and linear Budd fricition law is friction laws are applied only to the inferred state $I_{R_{\gamma,100}}$ only.

start with an initialisation step in which three model states - hereinafter referred to as inferred states - with different initial basal shear stress and viscosity fields are constructed from available observations, before being submitted to undergoing a 15-year relaxation period. Then, following the same procedure as the one described in Brondex et al. (2017) for each of these three inferred states, we identify the distributions of the friction coefficients of the aforementioned friction laws so that the basal shear stress field computed with these laws is the same as the one obtained at the end of the 15-year relaxation period. After this-For the two Weertman laws and the two Schoof laws, this procedure is repeated for each of the three inferred states. In contrast, because they imply a dependence of $|\tau_b|$ on N over the whole grounded part of the domain, we consider the two Budd laws as being less physically acceptable so that, for these laws, the identification procedure is performed for one of the inferred states only due to limited computational resources. Therefore, after the identification step, we are left with 13-14 new model states, hereinafter referred to as initial states, corresponding to four friction laws - the linear and non-linear Weertman laws and the non-linear Schoof laws with $C_{max} = 0.4$ and $C_{max} = 0.6$ - applied to the three inferred states as well as the Budd law-linear and non-linear Budd laws applied to one of the inferred state-states only. These 13-14 initial states constitute the starting points of a set of two 100+5 year pronostic simulations, i.e. an unperturbed control run and a run for which the oceanic melt rate is perturbed. Given the size of the domain and the mesh refinement required to capture essential flow features, each pronostic simulation has a numerical cost of around 11000 CPU hours. Figure 2 summarises all the consecutive steps of the experimental setup, which are described in details below.

10 2.2.1 Initialisation

A number of observations are used in order to initialise the model. The initial ice thickness is taken from Bedmap2 (Fretwell et al., 2013). ~~We use the ice temperature map of Antarctica established by Van Liefferinge and Pattyn (2013) in order to calculate a reference viscosity field $\eta_{0,ref}$ from Eqs. (3) and (4)~~ A two-dimensional reference field of $\bar{\eta}_0$, denoted $\bar{\eta}_{0,ref}$, is computed using a three-dimensional ice temperature field of Antarctica (Van Liefferinge, personal communication) obtained using a thermo-mechanical model forced with a mean geothermal heat flux (Van Liefferinge and Pattyn, 2013). In addition, we use the observed surface velocities of Rignot et al. (2011) ~~in order to formulate an inverse problem to invert for basal shear stress and ice rheology~~. These velocities are given on each ~~nodes~~ node of a regular grid with a 450 m resolution, except in some regions, sometimes very wide, over which the information is missing. The estimated error on the norm of observed velocities ranges, depending on regions, between 1 m a^{-1} and 17 m a^{-1} . These observations have been collected over periods spanning several years, which could potentially induce inconsistencies in regions where the flow features are evolving rapidly.

5 The flow solution \mathbf{u} of the SSA equations (1) depends on both the basal shear stress field and the effective viscosity field. For simplicity, the initial basal shear stress field is computed with a linear Weertman law of which we infer the friction coefficient distribution \hat{C}_W . Although ~~$\eta_{0,ref}$ constitutes $\bar{\eta}_{0,ref}$ enables to get~~ a first approximation of ~~ice~~ the effective viscosity, there are significant uncertainties regarding the temperature ~~map of Van Liefferinge and Pattyn (2013) field used to derive this field~~ as well as the parameters linking the ~~ice fluidity rate factor of ice~~ to its temperature. In addition, ice viscosity does not depend

10 only on temperature but also on several other parameters including damage, anisotropy, water content, density, grain size and ~~impurities~~ impurity content (Cuffey and Paterson, 2010). Therefore, the question is ~~wether~~ whether the local discrepancies between observed and modelled velocities at any given point of the domain should be attributed to an inappropriate basal shear stress field or to errors on the reference ~~viscosity field $\eta_{0,ref}$ field $\bar{\eta}_{0,ref}$~~ . Indeed, several model states consistent with observations can be constructed, for which the fit between modelled and observed velocities is obtained by adjusting rather

15 the basal shear stress or rather the viscosity. In order to assess the sensitivity of the results to the initialisation strategy, we construct three inferred states - denoted ~~I_{SV}~~ $I_{B_{\infty}}$, $I_{R_{\gamma,100}}$ and $I_{R_{\gamma,1}}$ - by means of the control method, building on the approach described in Fürst et al. (2015).

The total cost function J_{tot} to minimise includes two cost functions and two Tikhonov regularisation terms:

$$J_{tot} = J_v + \lambda_{div} J_{div} + \lambda_{reg,\alpha} J_{reg,\alpha} + \lambda_{reg,\gamma} J_{reg,\gamma}. \quad (15)$$

20 The misfit between modelled (\mathbf{u}) and observed (\mathbf{u}_{obs}) velocities is comprised in the first cost term J_v . To avoid errors due to interpolation of observed velocities at the model mesh nodes, J_v is a discrete sum evaluated directly at the observation points. It reads:

$$J_v = \frac{1}{2} \sum_{i=1}^{N_{obs}} (|\mathbf{u}_{i,obs} - \mathbf{u}_i|)^2, \quad (16)$$

where N_{obs} is the total number of available observations, $\mathbf{u}_{i,obs}$ the velocity observed at point i and \mathbf{u}_i the modelled velocity, which is interpolated at the observation point i . The second cost function J_{div} is intended to penalise the large gaps between

25

ice flux divergence and mass balance, leading to inferred states closer to steady states. It reads:

$$J_{div} = \frac{1}{2} \int_{\Gamma} \left(\frac{\partial(uH)}{\partial x} + \frac{\partial(vH)}{\partial y} - (a_s - a_b) \right)^2 d\Gamma, \quad (17)$$

where Γ is the model domain. During the inversion, we actually optimise the variables α and γ , which are related to τ_b and η , respectively, the linear Weertman law coefficient and the viscosity $\bar{\eta}_0$, respectively, as follows:

$$\hat{C}_W = 10^\alpha, \quad (18)$$

and

$$\underline{\eta} \bar{\eta}_0 = \frac{\gamma^2}{R_\gamma} \underline{\eta} \bar{\eta}_{0,ref}, \quad (19)$$

where R_γ is a constant. The variable changes (18) and (19) prevent non-physical negative values of basal shear stress and viscosity, respectively. In addition, the variable change (19) enables to tune the relative weight that will be put on basal shear stress and viscosity during inversion. Indeed, the minimisation of the cost functions relies on the calculation of their gradients with respect to the variables to optimise (MacAyeal, 1993). As a consequence, the highest the value attributed to R_γ the lowest the gradients of J_v and J_{div} calculated with respect to γ relatively to the ones calculated with respect to α . In such a case, the distribution of α - and thus of the basal shear stress - will be more affected (on the grounded part only as τ_b is forced to zero wherever ice is floating) than for lower values of R_γ . The two regularisation functions $J_{reg,\alpha}$ and $J_{reg,\gamma}$ in turn penalise first spatial derivatives of, respectively, α and γ . They are meant to avoid overfitting the velocity observations and thus, to improve the conditioning of the problem.

Among the three inferred states considered in this study, the two states $I_{R_\gamma,100}$ and $I_{R_\gamma,1}$ are constructed by optimising both α and γ with, respectively, $R_\gamma = 100$ and $R_\gamma = 1$ in Eq. (19). Hence, more weight is put on basal shear stress to the detriment of viscosity for $I_{R_\gamma,100}$ than for $I_{R_\gamma,1}$. In contrast, the inferred state $I_{SV-I_{R_\gamma,\infty}}$ is obtained by optimising α only, while the viscosity is forced to $\eta_0 = \eta_{0,ref} \bar{\eta}_0 = \bar{\eta}_{0,ref}$. The gradients of J_{tot} are derived following the adjoint method (MacAyeal, 1993), while the minimisation itself is done using the quasi-Newton routine M1QN3 (Gilbert and Lemaréchal, 1989). The minimisation method being an iterative method, we need to provide initial guesses for the distributions of the variables to optimise. Following Fürst et al. (2015) Morlighem et al. (2013), the initial guess for α is found by considering that, as a first approximation, the driving stress is exactly compensated by the basal shear stress at any given point of the ice/bed interface. Regarding the initial field of viscosity $\bar{\eta}_0$, it is simply set to $\eta_{0,ref} \bar{\eta}_{0,ref}$ for both $I_{R_\gamma,100}$ and $I_{R_\gamma,1}$.

For each of the three inferred states, we follow a L-curve approach as described in Fürst et al. (2015) to retrieve the optimal values of λ_{div} , $\lambda_{reg,\alpha}$ and $\lambda_{reg,\gamma}$ (only for $I_{R_\gamma,100}$ and $I_{R_\gamma,1}$) leading to inferred states showing good compromise between smooth distributions of α and γ , low differences between ice fluxes and mass balance and good fit between observed and modelled velocities. We find, respectively, $(5.1 \times 10^{-5}, 7.1 \times 10^5)$ for $I_{SV-I_{R_\gamma,\infty}}$, $(5.9 \times 10^{-5}, 2.5 \times 10^6, 1.4 \times 10^6)$ for $I_{R_\gamma,100}$, and $(1.8 \times 10^{-5}, 5.4 \times 10^6, 4.7 \times 10^5)$ for $I_{R_\gamma,1}$.

Although strong discrepancies between mass balance and ice flux are penalised through J_{div} in Eq. (15), the three inferred states are not exactly steady states. Seroussi et al. (2011) and Gillet-Chaulet et al. (2012) have reported the occurrence

occurrence of non-physical ice thickness rates of change in the first years following inversion. These ice flux anomalies are
 30 due to uncertainties on the model initial conditions, in particular regarding the prescribed topography and the values attributed
 to the various parameters, and are usually dissipated within a few years. For this reason, each of the three inferred states ~~is~~
~~submitted to~~ undergoes a relaxation period, the duration of which is arbitrarily fixed to 15 years. These relaxations are per-
 formed with the direct model as described in Sect. 2.1, the basal shear stress field being computed through the linear Weertman
 law (see Fig. 2).

2.2.2 Identification of friction laws coefficients

For each of the three inferred states, the 15-year relaxation period leads to a new state characterised by a new velocity field,
 5 which we denote $\hat{\mathbf{u}}_b$, as well as a new basal shear stress field, denoted $\hat{\boldsymbol{\tau}}_b$. These two fields relate to each other through the
 linear Weertman law, i.e. Eq (5) with the inferred friction coefficient \hat{C}_W (which depends on the considered inferred state) and
 $m = 1$. As thoroughly described in Brondex et al. (2017), these two fields can be used to analytically identify the distribution
 of the friction coefficient of ~~another law~~ other laws, which would lead to the same reference basal shear stress field $\hat{\boldsymbol{\tau}}_b$. Thus,
 the distributions of the friction coefficient of the non-linear Weertman law, the ~~non-linear Budd law and the Schoof law~~ two
 10 Budd laws and the two Schoof laws can be identified by solving, respectively:

$$C_{W,nl} = \hat{C}_W |\hat{\mathbf{u}}_b|^{1-m}, \quad (20)$$

$$C_B = \hat{C}_W \frac{|\hat{\mathbf{u}}_b|^{1-m}}{\hat{N}}, \quad (21)$$

and,

$$15 \quad C_S = \frac{|\hat{\boldsymbol{\tau}}_b|}{|\hat{\mathbf{u}}_b|^m \left(1 - \left(\frac{|\hat{\boldsymbol{\tau}}_b|}{C_{max} \hat{N}} \right)^{1/m} \right)^m}. \quad (22)$$

For the Budd and Schoof laws, the effective pressure field \hat{N} used for the identification is calculated through Eq. (8) from
 the geometry obtained at the end of the relaxation period. Note that the fields \hat{C}_W , $\hat{\mathbf{u}}_b$, $\hat{\boldsymbol{\tau}}_b$ and \hat{N} being dependent of the
 inferred state, these identifications are repeated for each one of the three inferred states, except for the ~~Budd law linear and~~
~~non-linear Budd laws~~ for which the ~~identification has~~ identifications have been done only for the case $I_{R_{\gamma,100}}$ (see Fig. 2).
 Equations (20) and (21) enable to identify the friction coefficients of, respectively, the non-linear Weertman ~~and law and the~~
~~two~~ Budd laws at every grounded ~~nodes~~ node covered with ice. At floating nodes or in the very few places of the domain
 which are ~~ice free~~ ice-free when identification is performed, these coefficients are arbitrarily fixed to, respectively, $C_{W,nl} =$
 5 $10^{-6} \text{ MPa m}^{-1/3} \text{ a}^{1/3}$ and $C_B = 10^{-6} \text{ m}^{-1/3} \text{ a}^{1/3}$. This choice does not appear to be critical as all the following prognostic
 experiments lead exclusively to a GL retreat.

In contrast, because the Schoof law was constructed so that Iken's bound is satisfied (Schoof, 2005), Eq. (22) has a solution
 only in places where $|\hat{\boldsymbol{\tau}}_b|/\hat{N} < C_{max}$. Figure 3 shows, for each of the three inferred states, the percentage of grounded nodes

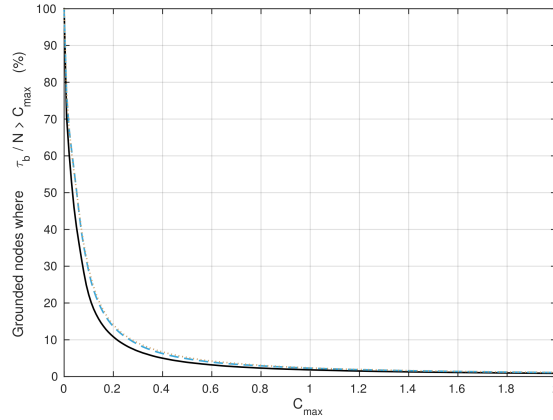


Figure 3. Percentage of grounded nodes where Iken’s bound is not satisfied as a function of the value attributed to the parameter C_{max} , for the inferred states I_{SV} - $I_{B_{\infty}}$ (black solid line), $I_{R\gamma,100}$ (blue dashed line) and $I_{R\gamma,1}$ (brown dotted line).

where the value of C_S cannot be identified directly from Eq. (22), depending on the value attributed to the parameter C_{max} .

10 Although we do not expect the parameter C_{max} to be uniform all over the bed model domain, there is currently no way to constrain its spatial distribution. As a consequence, two different uniform values are considered: $C_{max} = 0.4$ and $C_{max} = 0.6$. Note that the identification of C_S has then to be done for each of the two values of C_{max} . Because the sensitivity of basal shear stress to C_S is very small in places close to flotation, the identification of C_S from Eq. 22 is only done at nodes where $|\hat{\tau}_b|/\hat{N} \leq 0.8C_{max}$. The values of C_S at nodes where $|\hat{\tau}_b|/\hat{N} > 0.8C_{max}$ are linearly interpolated from the closest

15 neighboring nodes. In addition, we arbitrarily set $C_S = 10^{-3} \text{ MPa m}^{-1/3} \text{ a}^{1/3}$ in places which are ice-free ice-free or where ice is afloat when the identification is performed. Finally, we end up with six different distributions of C_S corresponding to the two values of C_{max} applied to the three inferred states I_{SV} - $I_{B_{\infty}}$, $I_{R\gamma,100}$ and $I_{R\gamma,1}$. For these six distributions, the percentage of grounded nodes at which C_S has to be interpolated is comprised between $\sim 4\% \sim 4\%$ (for the initial state I_{SV} - $I_{B_{\infty}}$ associated to the parameter $C_{max} = 0.4$) and $\sim 8\% \sim 8\%$ (for the initial state $I_{R\gamma,1}$ associated to the

20 parameter $C_{max} = 0.6$, $C_{max} = 0.4$). As expected, the nodes at which an interpolation is required are the closest to flotation and, therefore, are mostly located right upstream the GL.

As stated previously, the identification steps lead to 13-14 different initial states, which are used as the starting points of the prognostic simulations (blue dots in Fig. 2).

2.2.3 Prognostic simulations

25 The 13-14 initial states are submitted to a set of two 105-year prognostic runs: (i) then run forward in time for 105 years under two different scenarios: (1) a control run (EXP_CONTROL) and (ii) a basal melt anomaly run (EXP_ABMB). The EXP_CONTROL run is an unforced forward experiment aiming at characterizing model drift, which depends both on the

initial state and the friction law. Therefore, all model parameters and forcing in EXP_CONTROL are the same as those used for initialisation and presented in Sect. 2.1.

The EXP_ABMB run consists in applying a synthetic anomaly of basal melting rate under floating ice, all other model parameters and forcing being kept the same as in EXP_CONTROL: after a first 5-year period free of any perturbation, a uniform basal melting rate anomaly $abmb$ of 13.2 m a^{-1} is progressively added to the initial basal melting rate a_b , given by Eq. (14), over the following 40 years of simulation. Thus, the basal melting rate $a_{b,ABMB}$ for this run is given by:

$$5 \quad \begin{cases} a_{b,ABMB} = a_b & \text{if } 0 \leq t < 5 \text{ a} \\ a_{b,ABMB} = a_b + abmb \frac{\text{floor}(t)-5}{40} & \text{if } 5 \leq t < 45 \text{ a} \\ a_{b,ABMB} = a_b + abmb & \text{if } t \geq 45 \text{ a.} \end{cases} \quad (23)$$

The basal melting rate anomaly $abmb$ corresponds to the one prescribed for the ASE within the InitMIP-Antarctica framework (Nowicki et al., 2016).

3 Results

3.1 Initialisation

- 10 The three inferred states $I_{SV} I_{B_{\infty}}$, $I_{R_{\gamma,100}}$ and $I_{R_{\gamma,1}}$ are compared in Fig. 4. The absolute difference between modelled \mathbf{u} and observed \mathbf{u}_{obs} velocities turns out to get smaller when both basal shear stress and viscosity are inferred (Fig. 4a-c). This is particularly true for the ice shelves, which do not feel any basal shear stress: although the basal shear stress right upstream the GL do influence velocities within the downstream ice shelf, the most efficient way to get a better match between modelled and observed velocities in floating areas is through a local ~~adjustement~~ adjustment of viscosity. Thus, the inferred state I_{SV}
- 15 $I_{B_{\infty}}$ shows important errors on the Pine Island, Thwaites and, to a lesser extent, Crosson ice shelves (Fig. 4a). The root mean squared (RMS) errors obtained for the inferred states $I_{SV} I_{B_{\infty}}$, $I_{R_{\gamma,100}}$ and $I_{R_{\gamma,1}}$ are, respectively, 85.5 m a^{-1} , 52.4 m a^{-1} and 37.5 m a^{-1} .

- The ratio between the norm of the basal shear stress and the norm of the driving stress is shown in Fig. 4d-f. In addition, plots of the norm of the basal shear stress obtained for the three inferred states are included in the supplementary material
- 20 (Fig. S1) to allow for comparison with previous work in which inversions of basal shear stress in the regions of PIG and Thwaites were performed (Joughin et al., 2009; Morlighem et al., 2010). At the end of the inversions, there are several regions where the local driving stress is not entirely compensated by the local basal shear stress (blue regions). As expected, these regions correspond to regions of rapid flow; in particular, Pine Island Ice Stream can be easily distinguished. The regions of low τ_b gets narrower as more weight is put on viscosity during inversion. Indeed, when the viscosity is inferred, another way
- 25 for the inversion ~~algorithmn~~ algorithm to increase the modelled velocities in areas where they would be too low otherwise is to soften the ice locally: this is the case, for example, in the higher part of PIG, in particular for the inferred state $I_{R_{\gamma,1}}$ for which the inversion algorithm induces a local reduction of viscosity rather than of the basal stress to increase the modelled velocities (panels f and i of Fig. 4). It is also this same mechanism which is behind the low viscosity bands ~~which can~~

~~easily be distinguished~~, easily distinguishable in Fig. 4h (note that they are also present in Fig. 4i but less visible due to the wider color scale). These soft bands correspond to shear margins ~~where shear stresses are high and, therefore, ice is strongly damaged. The correlation between highly fractured areas and locally reduced viscosity has already been showed in several previous studies (Vieli et al., 2006, 2007; Khazendar et al., 2007; Borstad et al., 2012, 2013)~~, where high shear stresses induce a local reduction of ice viscosity through different physical processes, including damage, strain heating and the development of crystalline fabric (e.g. Borstad et al., 2013; Bondzio et al., 2017; Minchew et al., 2018). On the contrary, the inversion algorithm can render the ice locally stiffer in order to decrease the modelled velocities in areas where they are too high compared to observations, which is typically the case for ice shelves.

5 Because the model states obtained after the initialisation step are not steady states, they drift toward new states during the following 15-year relaxation period. Overall, the three inferred states show similar evolution patterns with relatively moderate ice thickness changes, except for the Pine Island and Thwaites ice shelves, where ice thickness increases of about 100 m over the 15 years. In contrast, ice streams get slightly thinner, ~~loosing~~ losing a few tens of m of ice in some places. At the end of the relaxation period, the thickness rates of change have decreased to physically acceptable values for all the inferred states, with, at most, 30 m a^{-1} of absolute thickness rate of change, concentrated within very localised areas; elsewhere, ice thickness is nearly at equilibrium with, at most, a few m a^{-1} of absolute thickness rate of change. Although the modelled velocity structure remains similar to observations, the RMS errors between observed velocities and velocities computed at the end of the relaxation period have risen to 124.8 m a^{-1} , 119.4 m a^{-1} and 96.4 m a^{-1} for, respectively, $I_{SV}I_{B_{\infty}}$, $I_{R_{\gamma,100}}$ and $I_{R_{\gamma,1}}$.

3.2 Identification of friction laws coefficients

15 For each of the three inferred states, the basal shear stress fields computed with the non-linear Weertman ~~and law and with the two~~ Budd laws using the friction coefficient distributions deduced through, respectively, Eqs. (20) and (21) are identical to the basal shear stress field $\hat{\tau}_b$ used for the identifications. In contrast, because the value of C_S cannot be exactly identified through Eq. (22) at every grounded ~~nodes~~ node but need to be interpolated in some places, $\hat{\tau}_b$ is not perfectly reproduced with the Schoof law. Figure 5a-c show an enlargement of regions within which the relative differences between the basal shear stress field calculated with the non-linear Schoof law (7) associated to $C_{max} = 0.4$ and to the C_S distributions identified through Eq. (22) or interpolated, which is denoted τ_{bS04} , and the reference basal shear stress field $\hat{\tau}_b$ are the highest. As expected, the highest relative differences are obtained close to the ice shelves (shown in green in Fig. 5a-c), where the nodes are close to flotation and C_S needs to be interpolated. Elsewhere, the fields of τ_b produced by the two friction laws are numerically identical. The relative difference between τ_{bS04} and $\hat{\tau}_b$ at nodes where C_S is interpolated ~~seldom exceeds 10%~~ rarely exceeds 25 10%; higher differences (up to ~~100%~~ 100%) occur very locally at some of the last grounded nodes. The results obtained with the parameter $C_{max} = 0.6$ (not shown) are similar except that the nodes where the interpolation of C_S is required are fewer and, therefore, the regions ~~within~~ within which the relative difference between τ_{bS06} and $\hat{\tau}_b$ is not null are less extended. Note that in places where the relative difference is not null, the Schoof law systematically produces the weakest basal shear stress.

30 Although moderate and very localised, the differences between the basal shear stress fields computed with the linear Weertman law and the Schoof law induce ~~significant~~ significant differences on the recomputed velocity fields (Fig. 5d-f). These differences propagate from the regions showing the highest differences in terms of τ_b to the floating areas located right downstream (particularly distinguishable on Thwaites Ice Shelf). Indeed, the decrease of the total basal shear stress due to the interpolation of C_S close to the GL needs to be compensated elsewhere so that the global stress balance keeps being satisfied. Because the floating areas do not support any basal shear stress, the perturbation is transmitted to the front of ice shelves, unless it can be compensated by an increase of the buttressing effect through a contact on a pinning point or an increase of lateral stresses at shear margins in the case of confined ice shelves. This latter mechanism is well-illustrated in Fig. 5d-f, which

5 shows an important increase of velocities at the shear margins of PIG when the linear Weertman law is replaced by the Schoof law. Furthermore, it turns out that the relative differences ~~on~~ in the velocity field are more pronounced when more weight is put on basal shear stress during the initialisations. Indeed, when the inversion ~~focus~~ focuses on the basal shear stress field only (inferred state $I_{SV}I_{B_{\infty}}$), the ice flow is more sensitive to any perturbation of this field. Once again, the results obtained with the parameter $C_{max} = 0.6$ (not shown) are very similar with slightly lower relative differences between the velocity fields

10 calculated with the two laws.

Finally, the identification (22) being performed at mesh nodes, the ~~gaussian~~ Gaussian integration on elements induces small numerical errors on the recomputed velocity field. These numerical errors are concentrated in coarse mesh areas and correspond to the discrepancies of, at most, a few tens of percents observed further inland, in places where the differences in terms of τ_b are null (Fig. 5d-f). Similar numerical errors are observed within the same areas when the velocity fields produced with the

15 non-linear Weertman ~~and~~ law and the two Budd laws after the identification step are compared to \hat{u}_b .

3.3 Prognostic simulations

The evolution of the grounded ice area during the control run for the three inferred states and the various friction laws is shown in Fig. 6. A decrease (resp. an increase) of the grounded ice area reflects a retreat (resp. an advance) of the GL. After relaxation, the grounded ice area at $t = 0$ a differs depending on the considered inferred state: it ranges between 433400 km² for $I_{R_{\gamma,1}}$

20 and 434000 km² for $I_{SV}I_{B_{\infty}}$.

~~Independently~~ Irrespective of the chosen inferred state or friction law, the natural (i.e. unperturbed) evolution of the domain is toward a reduction of its grounded ice area: the Schoof law with $C_{max} = 0.4$ systematically gives the more pronounced GL retreat with a reduction of grounded ice area over the 105 a of the control run ranging between 5000 km² for $I_{R_{\gamma,1}}$ and 7700 km² for $I_{SV}I_{B_{\infty}}$. In contrast, the reduction of the grounded ice area obtained with the non-linear Weertman law ranges

25 between 2400 km² for $I_{R_{\gamma,100}}$ and 4300 km² for $I_{SV}I_{B_{\infty}}$. Note that the evolutions of the grounded ice area obtained with the two Weertman laws are very close to one another ~~all over the~~ over the entire 105 a of the control run while the two Schoof laws produce noticeably different evolutions from the beginning of the run, with the case $C_{max} = 0.6$ showing less GL retreat than the case $C_{max} = 0.4$. This ~~is very likely~~ could be partly due to the differences between \hat{u}_b and the velocity field recomputed with the Schoof law after initialisation, which are lower for $C_{max} = 0.6$ than for $C_{max} = 0.4$ as reported in Sect. 3.2. For the

30 inferred state $I_{R_{\gamma,100}}$, the Budd ~~law produces an intermediate result~~ laws produce intermediate results with a reduction of the grounded ice area of 3000 km² for the non-linear Budd law and of 4200 km² for the linear Budd law.

The results of the perturbation experiments EXP_ABMB are shown relative to the control simulation EXP_CONTROL (Fig. 7). We consider both the relative reductions of grounded ice area as well as the relative losses of volume above flotation (VAF), given in mm of sea level equivalent (SLE). For the inferred state $I_{SV-I_{R_{\infty}}}$, the grounded ice areas produced by the two Weertman laws at the end of EXP_ABMB are about 2000 km² larger than the ones produced by the two Schoof laws. The difference between the linear and non-linear Weertman laws or between the two Schoof laws ($C_{max} = 0.4$ and $C_{max} = 0.6$) is about ten times smaller (~ 200 km²). However, the differences in terms of VAF change are more significant with, respectively, 6 mm SLE of difference between the two Weertman laws and 3 mm SLE of difference between the two Schoof laws. For
5 comparison, the linear Weertman law and the Schoof law with $C_{max} = 0.4$ show 24 mm SLE of difference in terms of VAF loss at the end of EXP_ABMB. When the viscosity is adjusted during inversion (cases $I_{R_{\gamma,100}}$ and $I_{R_{\gamma,1}}$), the GL shows less retreat and the relative VAF losses are less important (Fig. 7b-c and Fig. 7e-f). In addition, the relative evolutions of VAF obtained with the Weertman laws get closer to the ones obtained with the Schoof laws, except for the experiment associated to the inferred state $I_{R_{\gamma,1}}$ and the linear Weertman law (Fig. 7e-f). Note that the Schoof laws produce more GL retreat and
10 more SLR contribution than the Weertman laws for the inferred states $I_{SV-I_{R_{\infty}}}$ and $I_{R_{\gamma,100}}$. On the contrary, for the inferred state $I_{R_{\gamma,1}}$, the grounded ice areas seem to stabilise around $t = 60$ a with the Schoof laws while they keep decreasing for a few more years with the Weertman laws, so that the grounded ice areas obtained with the two latter at the end of EXP_ABMB are slightly less than the ones obtained with the two former. Despite a very similar decrease in terms of grounded ice areas as the ones obtained with the two Schoof laws, the linear Weertman law predicts 8 mm SLE less VAF loss (Fig. 7f). For the inferred
15 state $I_{R_{\gamma,100}}$, the ~~Budd friction law shows a much stronger response~~ two Budd friction laws show much stronger responses to the basal melting rate perturbation than the four other laws: at the end of EXP_ABMB, it results in a grounded ice area ~~reduced by~~ reduction comprised between 13000 km² for the non-linear Budd law and 16600 km² for the linear Budd law relative to EXP_CONTROL, while the grounded ice area reduction ranges between 6300 km² and 8900 km² for the four other experiments. Likewise, the relative VAF loss obtained ~~with the Budd law~~ at the end of EXP_ABMB is of 25 mm SLE for the
20 linear Budd law and of 33 mm SLE for the non-linear Budd law, whereas it ranges between 6 mm SLE and 15 mm SLE for the other experiments. This dramatic response of the GL dynamics to the perturbation when ~~the a~~ Budd law is used is in line with the results reported in Brondex et al. (2017).

The GL positions obtained with the various initial states at the beginning and at the end of experiment EXP_ABMB are represented in Fig. 8. The GL produced with the two Schoof laws are almost systematically more retreated than the ones
25 produced with the two Weertman laws. On the other hand, the GL final positions obtained with the Schoof law associated to $C_{max} = 0.6$ (brown solid lines) are generally very close to the ones obtained with the Schoof law associated to $C_{max} = 0.4$ (green solid lines). Likewise, the GL final positions obtained with the linear Weertman law (cyan solid lines) are often very close to the ones obtained with the non-linear Weertman law (magenta solid lines), except for the inferred state $I_{SV-I_{B_{max}}}$ where the former is sometimes more advanced and sometimes more retreated than the latter. Note that this does not contradict
30 the previously mentioned result regarding the similar evolution of grounded ice areas obtained with the two Weertman laws

for $I_{SV}I_{B_{\infty}}$, as evolutions represented in Fig. 7 are relative to EXP_CONTROL while the GL positions reported in Fig. 8 are absolute. The spatial distribution of the GL retreat is ~~primary-primarily~~ controlled by the bed topography, as already reported by Seroussi et al. (2017). As a consequence, the Schoof and Weertman laws all give the same retreat patterns: the most pronounced retreats are observed in regions of gentle slope (particularly visible upstream of the Thwaites Ice Shelf) while the GL tends to wrap around prominences. However, for $I_{R_{\gamma,100}}$, the ~~pattern-patterns~~ of GL retreat obtained with the Budd ~~law-is significantly different than-laws are significantly different from~~ the ones obtained with the four other laws. Indeed, the final GL position obtained with the non-linear Budd law is the most advanced in the Thwaites region, where the other laws (especially the Schoof laws and the linear Budd law) induce important retreats. On the contrary, ~~the Budd law induces both the linear and non-linear Budd laws induce~~ retreats of several tens of km in the regions of Cosgrove and Dotson Ice Shelves, where the four other laws give very similar final GL positions with limited retreat (especially in the Cosgrove Ice Shelf region).

The initial and final ice-sheet profiles obtained with the Schoof and non-linear Budd laws are represented in Fig. 9, along four selected flowlines (reported in white in Fig. 8b). By definition, wherever ice is grounded, the ice thickness comprised between z_s and the flotation altitude z_f , given by $z_f = (1 - \rho_w/\rho_i)b$, constitutes the thickness above flotation. Because the GL position is deduced from Eq. (11), it is located at the exact vertical of the point where $z_s = z_f$. Looking at the initial profiles, it turns out that the initial ice thickness above flotation increases rapidly upstream of the GL for the PIG and Thwaites flowlines. On the contrary, it increases very progressively as ~~going-we go~~ further upstream within the grounded part for the Dotson flowline, and even more so for the Cosgrove flowline. For all the considered flowlines, the bed profiles have sections of retrograde slope susceptible of giving rise to a MISI, unless it can be prevented by sufficient lateral buttressing (Gudmundsson et al., 2012). A MISI seems to occur for the Cosgrove and Dotson flowlines when the non-linear Budd law is used and for the PIG and Thwaites flowlines when the Schoof law is used. Note that the ice shelves of Cosgrove and Dotson have completely disappeared at the end of EXP_ABMB with both the Schoof and Budd laws. On the contrary, whatever the chosen law, PIG and Thwaites ice shelves are conserved until the end of the experiment, although they get thinner. A similar figure comparing the profiles obtained with the linear and non-linear Budd laws is available in the supplementary material (Fig. S2).

4 Discussion

Among the three inferred states, $I_{R_{\gamma,100}}$ appears to be the most physically acceptable one, despite a RMS error slightly higher than the one obtained for $I_{R_{\gamma,1}}$. Indeed, for $I_{R_{\gamma,100}}$, the inferred ~~viscosity- η_0~~ has been reduced, at most, by ~~84%-84%~~ (at the shear margins) and increased, at most, by ~~144%-144%~~ (very locally in the higher part of the Kohler Glacier, which feeds the Dotson ~~ice-shelve~~Ice Shelf) compared to the reference ~~viscosity- $\eta_{0,ref}$ field $\eta_{0,ref}$~~ . In contrast, for $I_{R_{\gamma,1}}$, ~~the inferred viscosity η_0~~ is at least 3 times higher than ~~$\eta_{0,ref}$ - $\eta_{0,ref}$~~ on large parts of the domain and more than 15 times higher in some very localised areas close to the Kohler Glacier (regions in red in Fig. 4i). Without considering any of the other parameters affecting the ice viscosity, such an increase could only be explained by a reduction of the ice temperature of several tens of degrees ~~eelsius~~Celsius (up to 50 °C in some regions) compared to the ~~temperature map of Van Liefvering and Pattyn (2013)-reference temperature field~~. On the other hand, even if ice was assumed to be at the melting point, the viscosity reduction observed

in some other parts of the domain (regions in blue in Fig. 4i) is non-physical. Note that for $I_{R_{\gamma,100}}$, an increase of the ice temperature of a few degrees only relative to the [solution of Van Liefferinge and Pattyn \(2013\) reference temperature field](#) is sufficient to explain the local reduction of ice viscosity observed in some regions (much less extended than for $I_{R_{\gamma,1}}$) after the inversion, except at the shear margins where the low viscosity bands can be attributed to the presence of damaged ice [and/or to strain heating and/or to anisotropy](#). Finally, the difference between modelled and observed velocities, especially on the ice shelves, are too high for the inferred state $I_{SV}I_{B_{\infty}}$.

The basal melting rate increase prescribed for the perturbation experiments EXP_ABMB induces a thinning of the ice shelves, which reduces their buttressing effect and causes a retreat of the GL. The amplitude of this retreat gets larger as more weight is put on basal shear stress to the detriment of viscosity during initialisation. Indeed, adjusting viscosity during initialisation leads to low viscosity bands at shear margins, which hamper the transfer of lateral stresses toward the interior of ice shelves and, from there, toward the ice streams which feed them. It follows that the model states for which viscosity is inferred are less sensitive to a reduction of the buttressing effect as the contribution of this effect to the initial global stress balance is less important than for $I_{SV}I_{B_{\infty}}$.

The different friction laws show different sensitivity to velocity and effective pressure - from no explicit dependence on N for the Weertman laws to an explicit dependence over the whole domain for the Budd [law-laws](#) - which leads to different evolutions of basal shear stress as the geometry of the domain evolves in response to the perturbation. Therefore, it is not surprising that, overall, grounded ice area evolutions and VAF losses show more sensitivity to the chosen friction law when more weight is put on basal shear stress to the detriment of viscosity during initialisation, i.e. for $I_{SV}I_{B_{\infty}}$ than for $I_{R_{\gamma,100}}$ or $I_{R_{\gamma,1}}$. The choice of the friction law affects not only the grounded ice area evolution, but also the evolution of ice thickness. Thus, [in some cases, two friction the grounded ice area shrinkage is more pronounced when using the linear Budd law rather than the non-linear Budd law, whereas the latter induces more VAF loss than the former. Similarly, although the linear and non-linear Weertman laws lead to similar evolutions of the grounded ice area but to for \$I_{B_{\infty}}\$ they produce significantly different VAF losses \(e.g. the linear and non-linear Weertman laws for \$I_{SV}\$, see panels a and d of Fig. 7\)](#). The Weertman laws systematically predict the lowest VAF losses. In addition, [as for the Budd laws](#), the linear Weertman law always predicts less VAF loss than the non-linear Weertman law, which is in line with the results of Ritz et al. (2015) showing a [highest-higher](#) contribution of the Antarctic ice sheet to SLR as the Weertman law tend toward a perfectly plastic law, i.e. $m \rightarrow 0$ in Eq. (5). The two Schoof laws lead to significantly higher VAF losses than the Weertman laws, with one exception: the non-linear Weertman law for the inferred state $I_{R_{\gamma,1}}$ which predicts a VAF loss very close to the ones obtained with the two Schoof laws. This is likely due to the fact that, for $I_{R_{\gamma,1}}$, there are several regions of unexpectedly high viscosity located a few tens of km upstream of the initial GL (Fig. 4i). Once the GL has reached these regions, ice is stiffer and hampers further retreat, which explains the stabilisation of grounded ice area seen in Fig. 7c. As a consequence, the rate of VAF losses obtained with the two Schoof laws decreases, which also occurs with the non-linear Weertman law but later on so that, at the end of EXP_ABMB, the relative VAF losses predicted by the three laws are almost identical. On the other hand, for the Schoof law, the [lowest-lower](#) the value of C_{max} the [highest-higher](#) the predicted VAF losses. This is not surprising as the regions over which friction is governed by a Coulomb regime when using a Schoof law gets wider when the value of C_{max} gets lower (Brondeix et al., 2017). For $I_{R_{\gamma,100}}$, the VAF

losses obtained with the ~~Budd law~~ two Budd laws are dramatically higher than the one obtained with the four other laws, which is in line with the results obtained in ~~our previous study~~ Brondex et al. (2017).

The sensitivity of ice thickness rates of change to the chosen friction law explains why the ~~Budd law produces~~ laws produce much larger GL retreat than the four other laws in the regions of Cosgrove and Dotson and, ~~conversely in the case of the~~ non-linear Budd law, less retreat in the Thwaites region. As shown in Brondex et al. (2017), because the Schoof law induces a Coulomb friction regime (i.e. $|\tau_b| \sim C_{max}N$) within a narrow region of a few km right upstream the GL, the buttressing loss due to basal melting rate increase cannot be compensated within this region, despite an increase ~~of in ice~~ in ice velocities. Therefore, the perturbation is transmitted upstream, in areas governed by a Weertman friction regime (i.e. $|\tau_b| \sim C_S|u_b|^m$), where a velocity increase enables a rapid compensation of the buttressing loss. As a consequence, although the Schoof law induces an important peak of thinning, it stays very localised in the immediate vicinity of the GL. In contrast, for the ~~Budd law~~ laws the basal shear stress depends on both u_b and N over the whole domain. In addition, N can be low on large distances upstream the GL, especially where the bed profile is retrograde and induces a rapid increase of the water column height as ~~going-we~~ go further upstream, while the ice thickness does not increase as fast. As a consequence, the peak of thinning obtained at the GL with ~~the a~~ Budd law is less pronounced than the one obtained with the Schoof law, but, depending on the bed profile, it can propagate much further upstream. This is particularly well-illustrated in Fig. 3 of Brondex et al. (2017). In ~~addition, as~~ for the Weertman law, perturbations are transmitted farther and faster inland when using the non-linear Budd law rather than the linear Budd law. As a consequence, the peak of thinning obtained with the linear Budd law in the immediate vicinity of the GL is slightly more pronounced than the one obtained with the non-linear Budd law, but it propagates over slightly shorter distances (Fig. S2 in the supplementary material). In the regions of Cosgrove and Dotson, the initial surface profiles are close to the flotation altitudes over large distances upstream the GL (Fig. 9). In these two regions, ~~the Budd law induces both the~~ linear and non-linear Budd laws induce a rapid purge of the VAF over these large distances, leading to ~~an~~ important retreat of the GL. This retreat might be enhanced by a potential MISI as the GL ends up on retrograde bed slopes. Note however that the Cosgrove and Dotson ice shelves being both well-confined, knowledge of the bed slopes alone is not sufficient to predict the ~~occurrence~~ occurrence of a MISI (Gudmundsson et al., 2012; Haseloff and Sergienko, 2018).

In contrast, Thwaites ice shelf is mostly unconfined and, at the beginning of the experiment, the GL lies at the downstream bound of a section of retrograde bed slope (solid black line in ~~the~~ the bottom left panel of Fig. 9). The initial thinning produced by the Schoof law in the very close vicinity of the GL is sufficient to induce a retreat within the reverse slope area, where a MISI likely ~~sets up~~ initiates. ~~The same goes for the linear Budd law (Fig. S2).~~ On the contrary, the thinning peak produced by the non-linear Budd law at the GL is not sufficient to induce a retreat of the latter over the 105 years of the experiment. Finally, the GL retreats obtained with the Budd and Schoof laws for PIG are more similar. This could be a consequence of the fact that the GL already lies on a retrograde slope at $t = 0$ a.

Although the differences in terms of GL dynamics and VAF losses obtained with the different friction laws tend to decrease as more weight is put on viscosity during inversion, they remain significant for the most physically acceptable inferred state, $I_{R_{\gamma,100}}$. In particular, the commonly used linear Weertman law predicts about 9 mm SLE less VAF losses at the end of the 105 years than the Schoof law, ~~which relies on a stronger physical basis~~.

~~The~~ In light of these results, using observations to constrain the form of the friction law which is best suited for a given application would constitute a huge leap towards the production of reliable projections of future SLR. Studies reporting the presence of soft sediments beneath PIG (e.g. Smith et al., 2013; Brisbourne et al., 2017) tend to support the use of a Schoof law in this region, as such a law induces a Coulomb friction regime in the vicinity of the GL. However, this does not constitute a validation of this law, neither does it provide any information regarding the spatial distributions of C_S and C_{max} . Because the basal stress must satisfy the global stress balance, constraining the form of the friction law would require observations at different times with significant differences in basal velocities, basal stresses and water pressure at the ice/bed interface. Unfortunately, these multiple sets of observations are not available or incomplete. In particular, the water pressure at the ice/bed interface is largely unknown and the assumption of perfect hydrological connectivity to the ocean is too gross for the purpose of constraining the form of the friction law.

More generally, the lack of a physically based subglacial hydrological model to compute effective pressure is the main limitation of the work presented here. Indeed, the water pressure calculated based on the assumption of perfect hydrological connectivity to the ocean might well be underestimated in some places as geothermal heat flux and frictional heating are known to cause basal melting, which is susceptible to build up water pressure at the ice/bed interface, especially in regions where the subglacial drainage system is inefficient (Colleoni et al., 2018). In addition, beside basal shear stress, ice viscosity is not the only poorly constrained field. In particular, there are important uncertainties regarding the bed elevation. Recently, Nias et al. (2018) derived new bedrock elevation and ice thickness maps of the PIG using a method based on the principle of mass conservation and compared these maps to the Bedmap2 data: they found substantial differences between the two, in particular right upstream the 1996 GL where a topographic rise has been removed with their new method. In addition, they ran the two obtained geometries forward in time to 50 years using four different friction laws, i.e. three Weertman laws with various values for the exponent m and a Tsai law with a Coulomb friction parameter set to 0.5, and showed that SLR projections are at least as sensitive to the accuracy of the bedrock topography and initial ice thickness as to the choice of the friction law.

5 Conclusion

The present study constitutes an extension of the sensibility analysis of GL dynamics and VAF loss predictions to the choice of a friction law presented in Brondex et al. (2017). Whereas the latter was based on a synthetic 2D flowline case, here we consider a real-world application, the Amundsen Sea Embayment, and therefore, have to address specific problems. First of all, the basal shear stress is not known and has to be deduced from observations of ice flow surface velocities through inverse methods. In addition, other model parameters are ~~uncertains~~ uncertain and can require to be adjusted based on observations. Thus, when ice viscosity is not inferred but ~~simply~~ deduced from available ice temperature ~~maps~~ fields, discrepancies between modeled and observed velocities are high, in particular within ice shelves. On the contrary, putting too much weight on viscosity to the detriment of basal shear stress during inversion lead to non-physical viscosity field. The inferred state $I_{R_\gamma,100}$ turns out to be the most physically acceptable of the constructed model states as it allows a good fit between observed and modelled velocities while showing a viscosity field closer to our expectations compared with $I_{R_\gamma,1}$.

30 Once the basal shear stress has been inferred, the friction coefficient distributions of the Weertman and Budd laws producing the same basal shear stress field with these laws can easily be identified. In contrast, by construction the Schoof law induces an upper bound on the computed basal shear stress equals to the value of the parameter C_{max} . This latter parameter accounts for till deformation and the values it can take are partly constrained by laboratory experiments. As a result, the value of C_S cannot be identified directly at nodes too close to flotation. This difficulty is overcome by interpolating (or extrapolating) the value of C_S at these nodes from the values at nodes where it can be directly identified. This procedure induces significant but very localised ~~, in particular within ice shelves,~~ discrepancies between the recomputed velocity field and the reference velocity field used for the identification, in particular within ice shelves.

5 The ~~schematic~~ perturbation experiments carried out following the identification step demonstrate a significant influence of the chosen friction law on GL dynamics and mass loss projections at a century timescale. In line with results obtained in our previous study, the VAF loss ~~projections produced~~ obtained with the commonly used Weertman law are systematically lower than the ones obtained with the Schoof law, which themselves are surpassed ~~by the projection in the simulations~~ carried out with the Budd ~~law-laws~~ (for $I_{R_{\gamma,100}}$). In addition, the Budd ~~law-laws~~ being dependent on effective pressure over the whole
10 grounded domain, ~~it induces they induce~~ GL retreat in places where the other tested laws do not. As for the Weertman laws, the non-linear Budd law induces more VAF loss than the linear Budd law. Although the differences between the results produced with the various law tend to decrease as more weight is put on viscosity during inversion, they keep being significant for the most physically acceptable model state constructed, i.e. $I_{R_{\gamma,100}}$.

In light of these results, we conclude that no reliable projection of future sea level rise can be obtained without the use of a
15 physically based friction law. Therefore, significant efforts still need to be put on getting a better understanding of the physical processes at play at the ice/bedrock interface in order to ~~constrain~~ constrain the form of the friction law ~~which that~~ needs to be used in models. In particular, the recognized importance of water pressure for basal sliding must be explicitly accounted for through the use of an effective pressure-dependent law, ~~but the latter ought to be fed by.~~ Because it implies a Coulomb friction regime at low effective pressure, which is best suited to model till deformation, we suggest to use the Schoof law rather than the
20 Budd law. However, the use of such a law adds the further difficulty of estimating the spatial distribution of water pressure at the ice/bed interface, which seems to be satisfactorily overcome only through a coupling of the ice flow model to a physically based subglacial hydrological model.

Code and data availability. Elmer/Ice code is publicly available through GitHub (<https://github.com/ElmerCSC/elmerfem>). All the simulations were performed with the version 8.2 (Rev: 997cb45) of Elmer/Ice. All scripts used for simulations and post-treatment as well as model output are available upon request from authors. The data used are listed in the references, except the surface mass balance, which is available
5 upon request from authors.

Author contributions. Julien Brondex, Fabien Gillet-Chaulet and Olivier Gagliardini designed the study. Fabien Gillet-Chaulet collected the data and prepared the experimental setup. Julien Brondex conducted the inversions, the identifications and the prognostic simulations. Julien Brondex wrote the paper with contributions from all co-authors.

10 *Competing interests.* Olivier Gagliardini is a member of the editorial board of the journal. All other authors declare that they have no competing interests.

Acknowledgements. This work was funded by the French National Research Agency (ANR) through the TROIS-AS (ANR-15-CE01-0005-01) project. J.B., F.G.C. and O.G. are part of Labex OSUG@2020 (ANR10 LABX56). Most of the computational resources were provided by CINES through the gge6066 project. Some of the computations were performed using the Froggy platform of the CIMENT infrastructure (<https://ciment.ujf-grenoble.fr>), which is supported by the Rhône-Alpes region (GRANT CPER07-13 CIRA), the OSUG@2020 labex
15 (reference ANR10 LABX56), and the Equip@Meso project (reference ANR-10-EQPX-29-01) of the programme Investissements d'Avenir supervised by the ANR.

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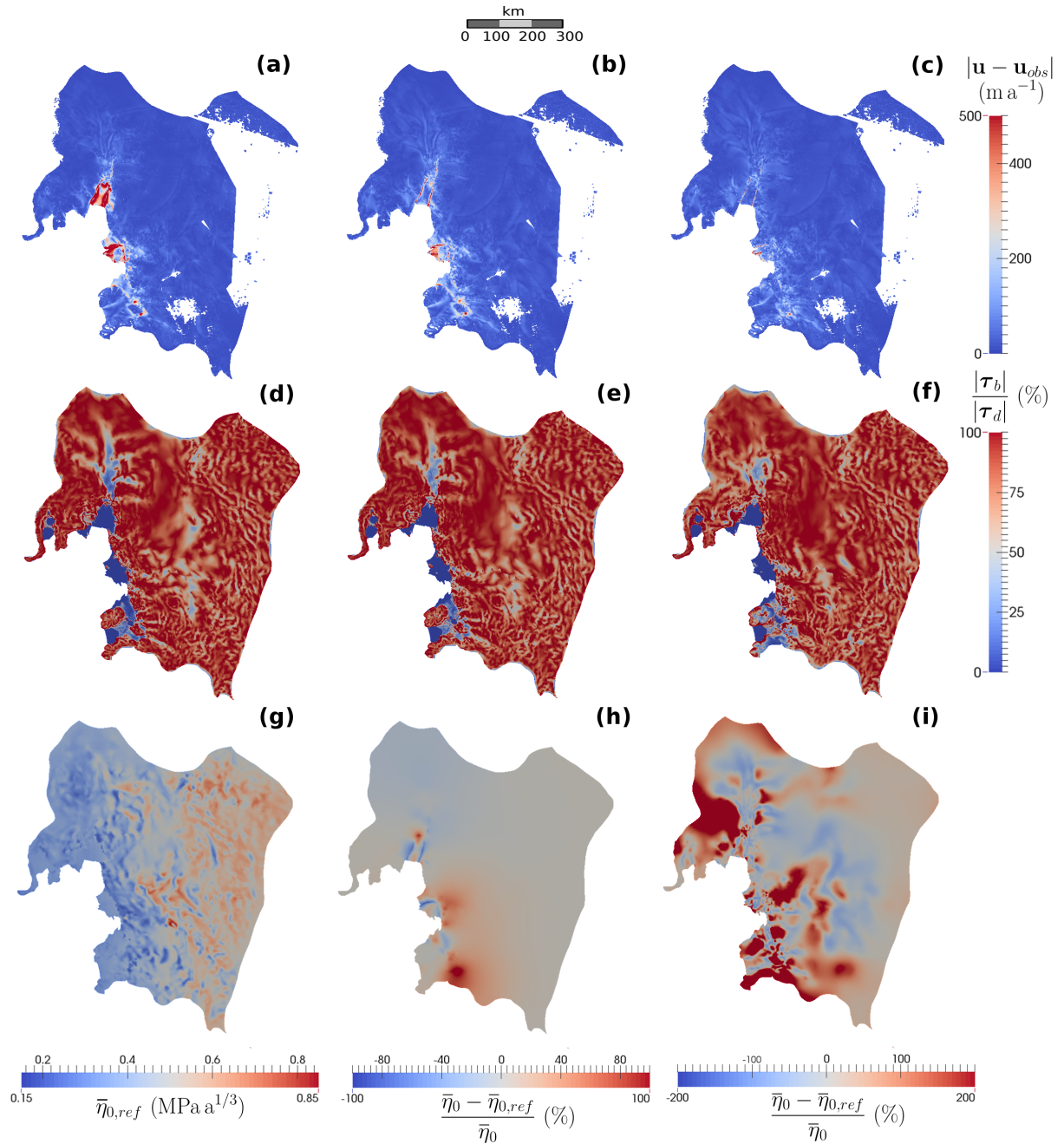


Figure 4. Comparison of inferred states $I_{SV} - I_{R_{\infty}}$ (first column), $I_{R_{\gamma,100}}$ (second column) and $I_{R_{\gamma,1}}$ (third column). For each of the three inferred states, the first row - panels (a), (b) and (c) - shows the absolute difference between modelled \mathbf{u} and observed \mathbf{u}_{obs} velocities (m a^{-1}); the second row - panels (d), (e) and (f) - show the ratio of the norm of τ_b relatively to the norm of τ_d ; the third row shows the reference viscosity $\eta_{0,ref}$ field $\bar{\eta}_{0,ref}$ ($\text{MPa a}^{1/3}$) for the inferred state $I_{SV} - I_{R_{\infty}}$ - panel (g) - as well as the relative difference between the reference viscosity $\bar{\eta}_0$ and the inferred viscosity $\bar{\eta}_{0,ref}$ for the inferred states $I_{R_{\gamma,100}}$ (second column) and $I_{R_{\gamma,1}}$ - panels (h) and (i), respectively. Note the different color scales for panels (h) and (i).

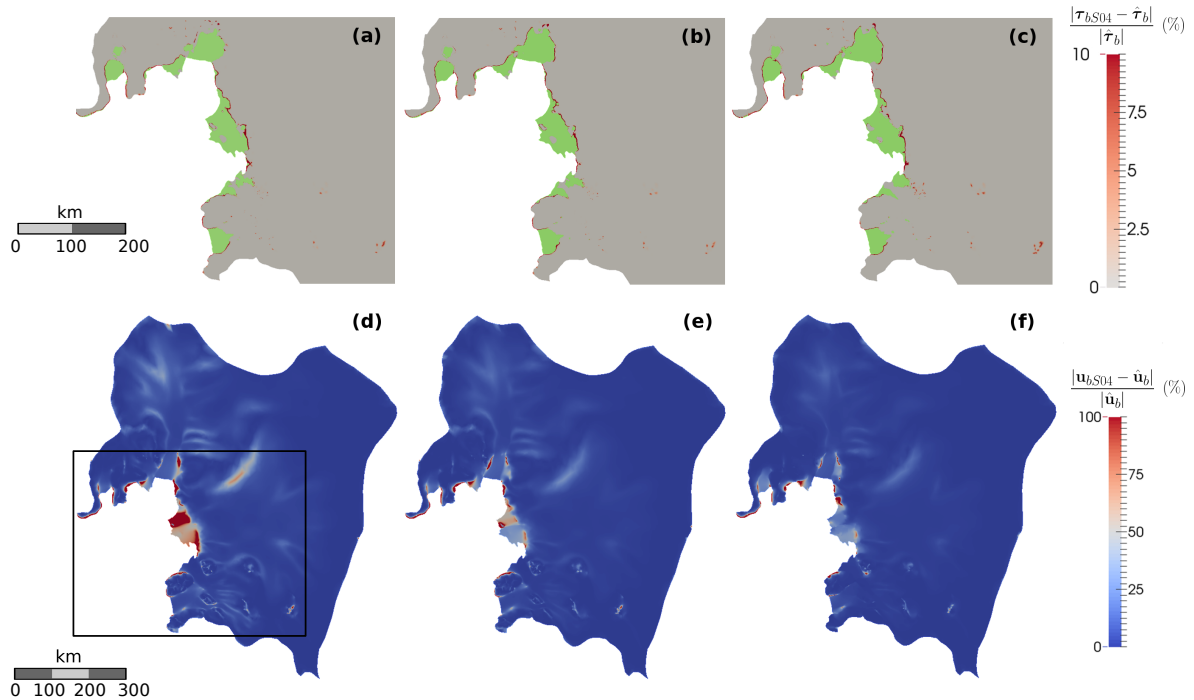


Figure 5. Relative differences (%) between the fields of τ_b (first row) and \mathbf{u}_b (second row) produced by the linear Weertman law and the non-linear Schoof law associated to $C_{max} = 0.4$ and to the C_S distributions identified through Eq. (22) or interpolated, for the inferred states $I_{SV}-I_{B_{\infty}}$ - panels (a) and (d) -, $I_{R_{\gamma,100}}$ - panels (b) and (e) - and $I_{R_{\gamma,1}}$ - panels (c) and (f). Figures of the first row zoom in the neighborings of ice shelves (shown in green), where the relative differences in τ_b are concentrated while figures of the second row show the whole ASE. The zoom in area is highlighted with a black box on panel (d).

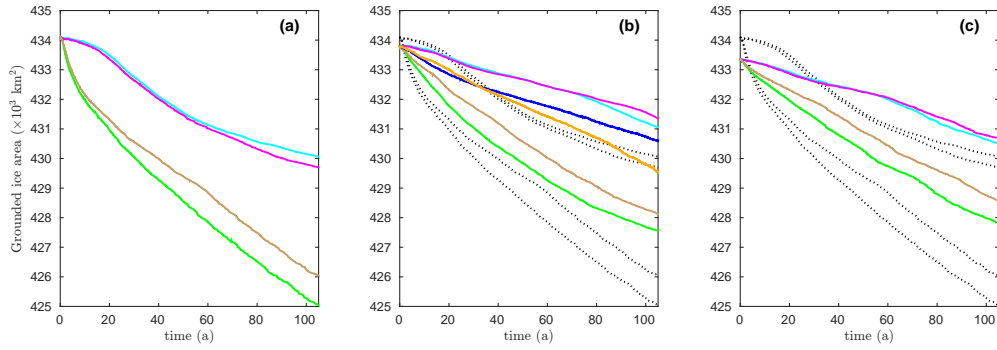


Figure 6. Evolution of grounded ice area ($\times 10^3 \text{ km}^2$) as a function of time during EXP_CONTROL for the inferred states (a) $I_{SV-I_{Bone}}$, (b) $I_{R_{\gamma,100}}$ and (c) $I_{R_{\gamma,1}}$ and the friction laws linear Weertman (cyan), non-linear Weertman (magenta), Schoof with $C_{max} = 0.4$ (green), Schoof with $C_{max} = 0.6$ (brown), linear Budd (orange, for the initial state $I_{R_{\gamma,100}}$ only) and non-linear Budd (blue, for the initial state $I_{R_{\gamma,100}}$ only). The results obtained with the various friction laws for the inferred state $I_{SV-I_{Bone}}$ are reported on (b) and (c) to ease comparison (black dotted lines).

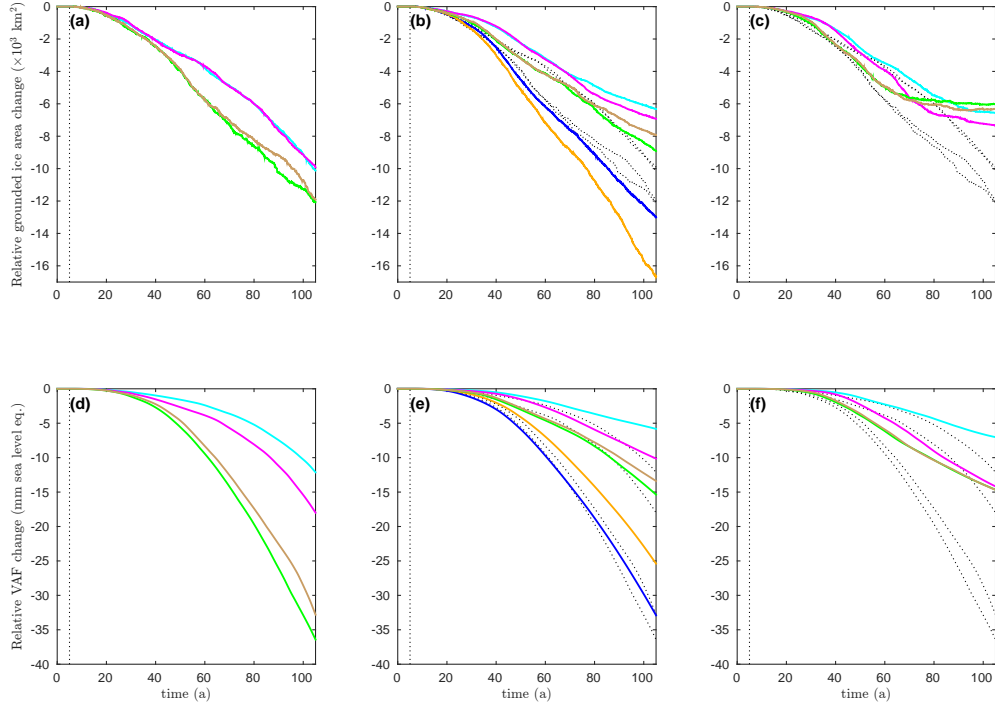


Figure 7. Evolution of grounded ice area in $\times 10^3$ km² (first row), and of volume above flotation in mm sea level equivalent (second row) as a function of time during EXP_ABMB (colored solid lines) relative to EXP_CONTROL for the inferred states $I_{SV} - I_{R_{ice}}$ - panels (a) and (d) -, $I_{R_{\gamma,100}}$ - panels (b) and (e) - and $I_{R_{\gamma,1}}$ - panels (c) and (f) - with the friction laws linear Weertman (cyan), non-linear Weertman (magenta), Schoof with $C_{max} = 0.4$ (green), Schoof with $C_{max} = 0.6$ (brown), linear Budd (orange, for the inferred state $I_{R_{\gamma,100}}$ only) and non-linear Budd (blue, for the inferred state $I_{R_{\gamma,100}}$ only). The results obtained with the various friction laws for the inferred state $I_{SV} - I_{R_{ice}}$ are reported on, respectively, (b)-(c) and (e)-(f) to ease comparison (black dotted lines). The vertical black dotted lines marks the introduction of the perturbation at $t = 5$ a.

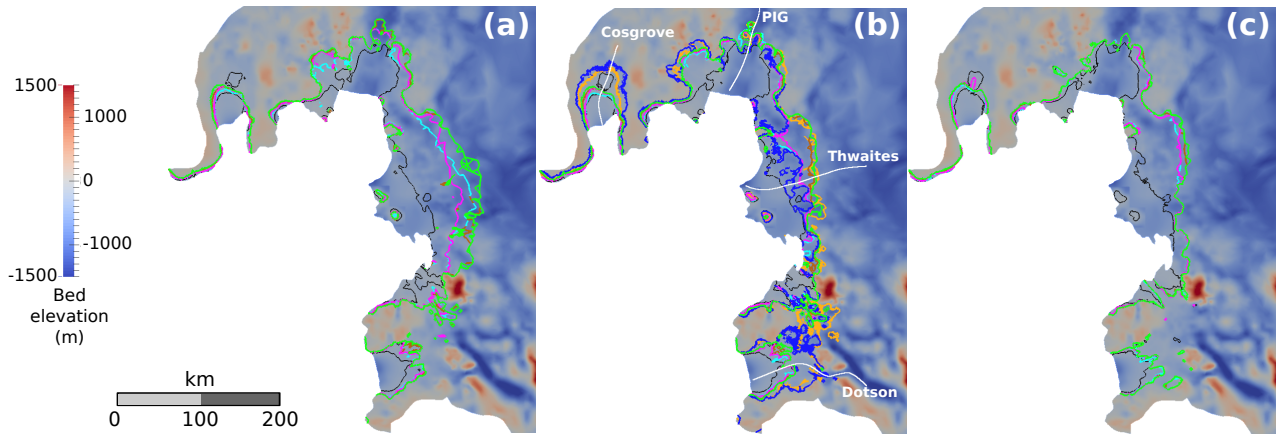


Figure 8. Bed elevation (m) and GL positions at the end of the experiment EXP_ABMB for the inferred states (a) $I_{sv} I_{R_{\infty}}$, (b) $I_{R_{\gamma, 100}}$ and (c) $I_{R_{\gamma, 1}}$ and the friction laws linear Weertman (cyan), non-linear Weertman (magenta), Schoof with $C_{max} = 0.4$ (green), Schoof with $C_{max} = 0.6$ (brown), linear Budd (orange, for the inferred state $I_{R_{\gamma, 100}}$ only) and non-linear Budd (blue, for the inferred state $I_{R_{\gamma, 100}}$ only). The GL position at $t = 0$ is reported for each of the three inferred states (solid black lines). The solid white lines in (b) correspond to flowlines at which ice-sheet profiles are represented in Fig. (9).

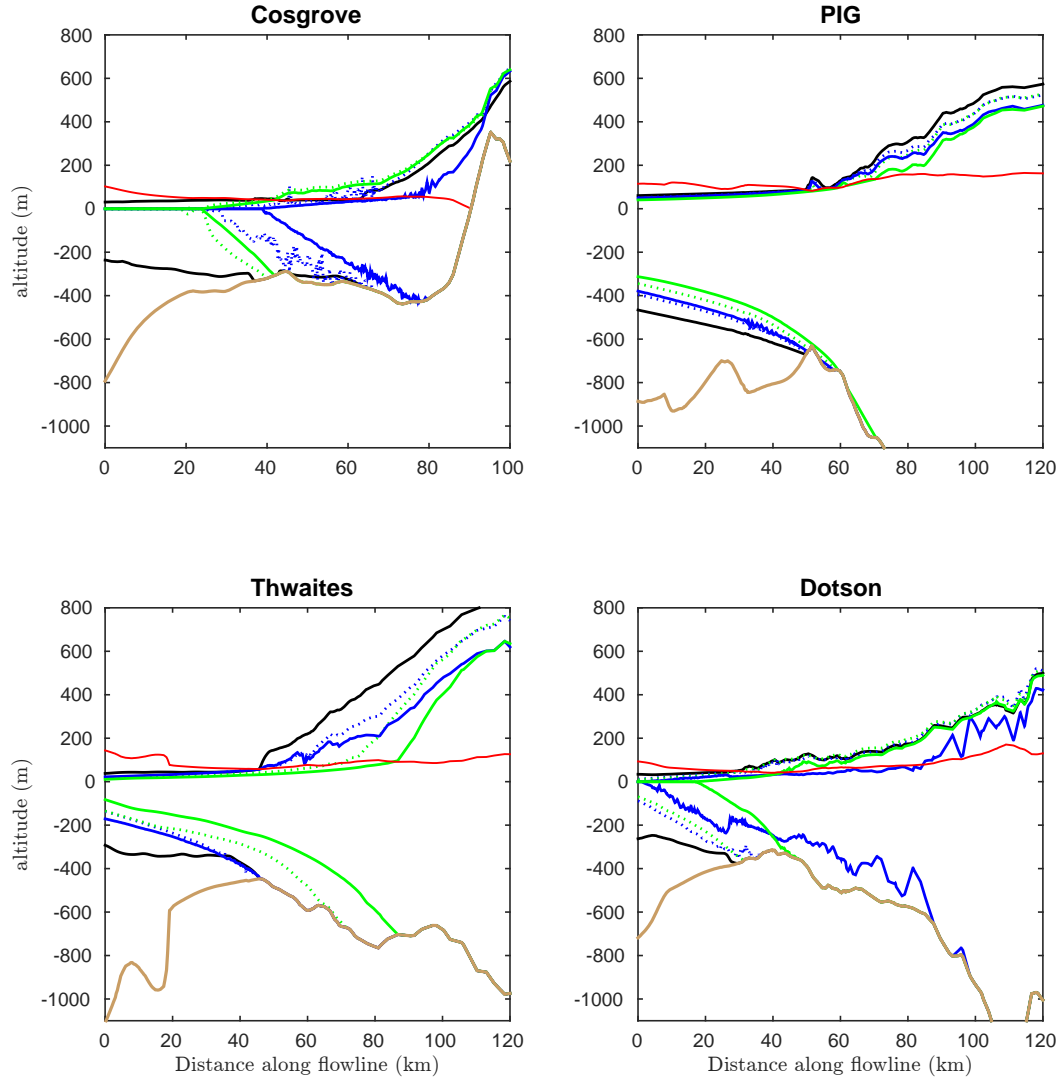


Figure 9. Ice-sheet profiles obtained for the inferred state $I_{R_\gamma, 100}$ at $t = 0$ a (black solid line), $t = 55$ a (colored dotted line) and $t = 105$ a (colored solid line) of EXP_ABMB with the Schoof law associated to $C_{max} = 0.4$ (green) and the non-linear Budd law (blue), along the flowlines reported in Fig. 8. The solid light brown line is the bed elevation. The red solid line is the flotation altitude z_f , i.e. the altitude of the top surface for which the ice-sheet is exactly at flotation given by $z_f = (1 - \rho_w / \rho_i)b$.

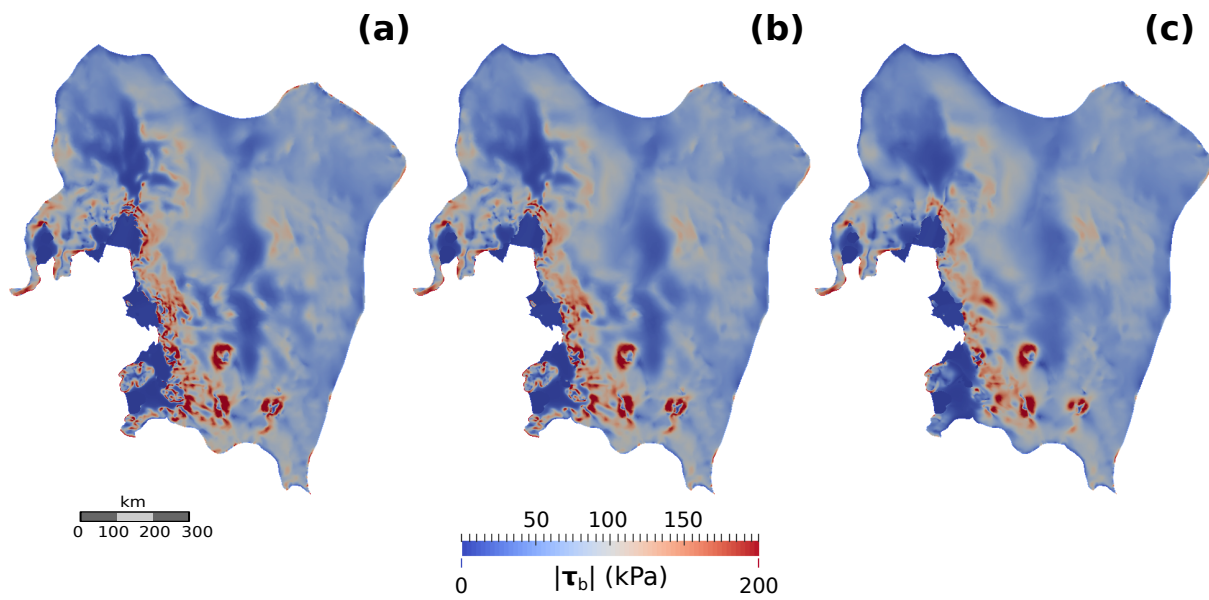


Figure S1. Norm of the basal shear stress field τ_b after inversion for the inferred states (a) $I_{R_{\gamma, \infty}}$, (b) $I_{R_{\gamma, 100}}$ and (c) $I_{R_{\gamma, 1}}$.

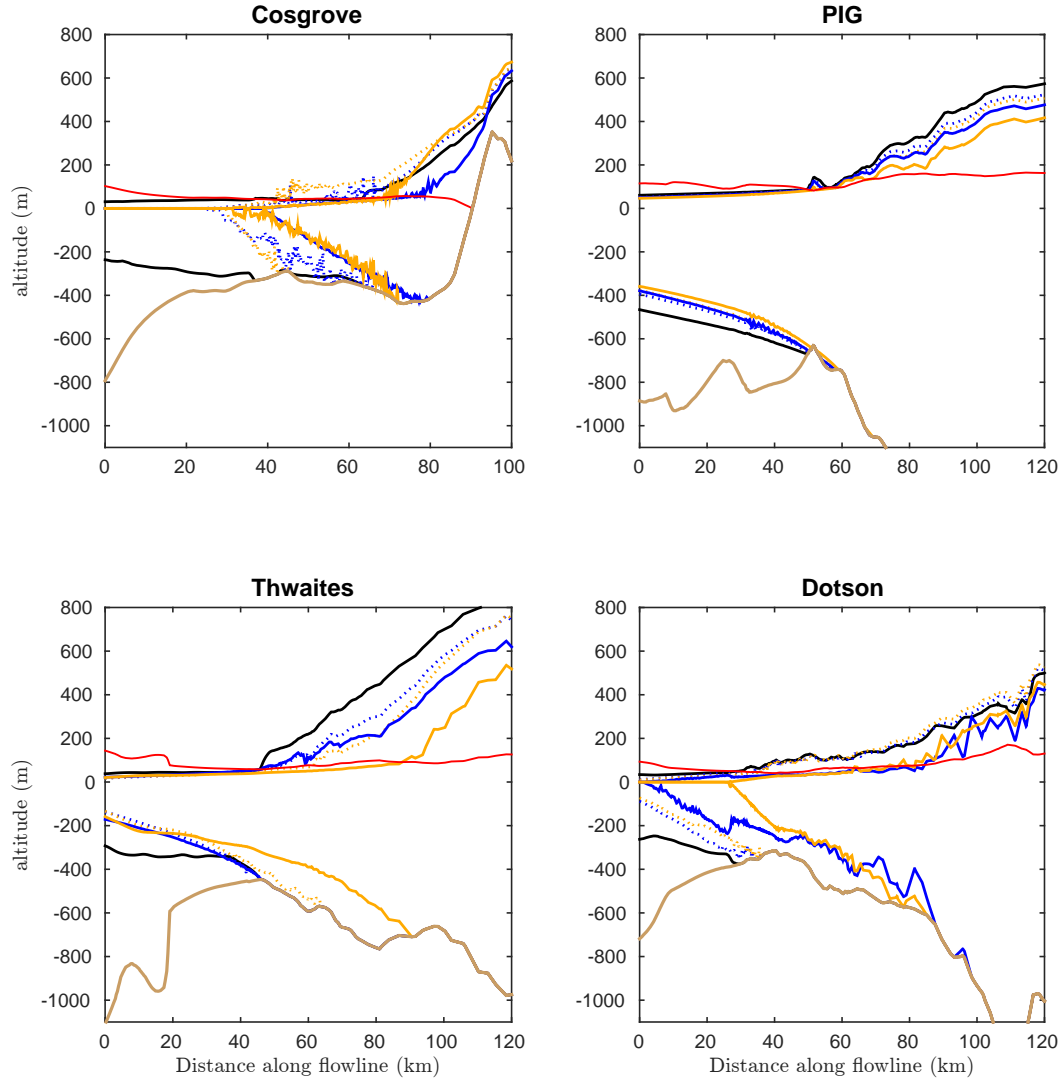


Figure S2. Ice-sheet profiles obtained for the inferred state $I_{R_{\gamma,100}}$ at $t = 0$ a (black solid line), $t = 55$ a (colored dotted line) and $t = 105$ a (colored solid line) of EXP_ABMB with the linear Budd law (orange) and the non-linear Budd law (blue), along the flowlines reported in Fig. 8. The solid light brown line is the bed elevation. The red solid line is the flotation altitude z_f , given by $z_f = (1 - \rho_w / \rho_i)b$.