Response Letter to Reviewer #1

Blue letters: revised and/or added text in the revised manuscript

~~Red letters~~ with strikethrough: deleted text in the revised manuscript

Text in *italic*: comments from the Reviewer #1

General Comments

Based on recent work (Millstein et al., 2022; Ranganathan et al., 2021) there is increasing interest in using n=4 rather than n=3 in ice sheet modelling. This paper uses 2D full-Stokes simulations with n=4 to provide order-of-magnitude constraints on the value of the fluidity parameter when n=4. They reduce the range of A from 6 orders of magnitude to 1. Generally, I think the paper provides a useful contribution to the community and should be published after the inclusion of a few more clarifying figures and paragraphs.

Authors' reply:

We sincerely appreciate Reviewer #1's cheerful and insightful comments. Our manuscript has been improved based on Reviewer #1's suggestions. We have included the responses and materials (e.g., figures and references) in this response letter.

Originality: The paper performs simple 2D simulations of regions of ice sheets. The novelty comes from using the value of n = 4 and exploring the range of A values in the rheology which give reasonable results. The main contribution is new constraints on the value of A to use when using n=4. This will be useful to ice sheet modellers interested in using this value of n, of which there is increasing interest in.

Authors' reply:

As Reviewer #1 correctly points out, we designed this study to narrow the range of A values for n = 4 using different Antarctic ice sheets and idealised slope models. We believe that our work can be a useful reference for the ice sheet modelling community in selecting A values when n = 4.

Scientific Quality: The authors use 2D full-stokes simulations to constrain appropriate value of A which give predictions which match observed velocities. The use of full-Stokes is good, and I am also pleased the authors demonstrate that the results are robust to a range of sliding exponents.

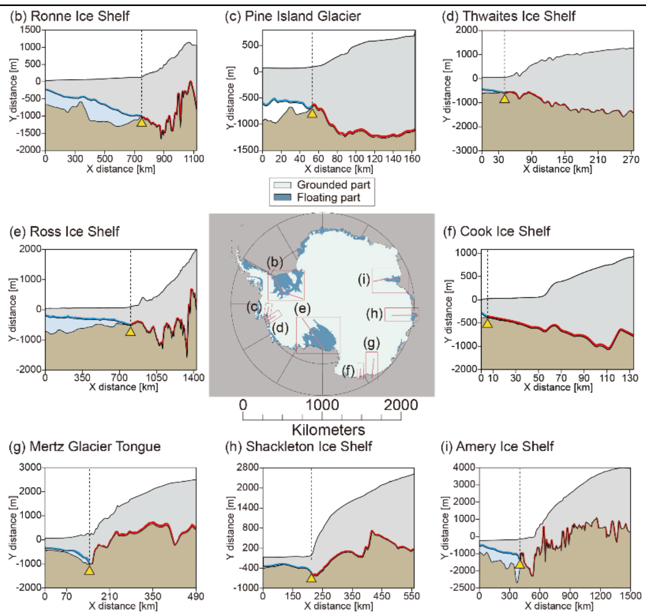
Authors' reply:

We appreciate the constructive feedback and positive evaluation of our work. To meet the high standards of numerical modelling in the ice sheet dynamics community, we recognised the need to test many parameters other than the A value, such as the sliding exponent. We have also done our best to perform the additional tests suggested by Reviewer #1, including 3D modelling of the idealised slope models.

One concern I have about the final range of A values given is that it may over-constrain A. The final range of A values stated, $t4.0o\ 16 \times 10^{-32}\ Pa^{-4}s^{-1}$, is found by simply combining the A values which give reasonable results for each case studied. One could imagine that if more ice shelves were included in this study, this method would give no A value which gave reasonable results for all. This is not a criticism of the work, which I think is valid, but just the calculation procedure used at the end.

Authors' reply:

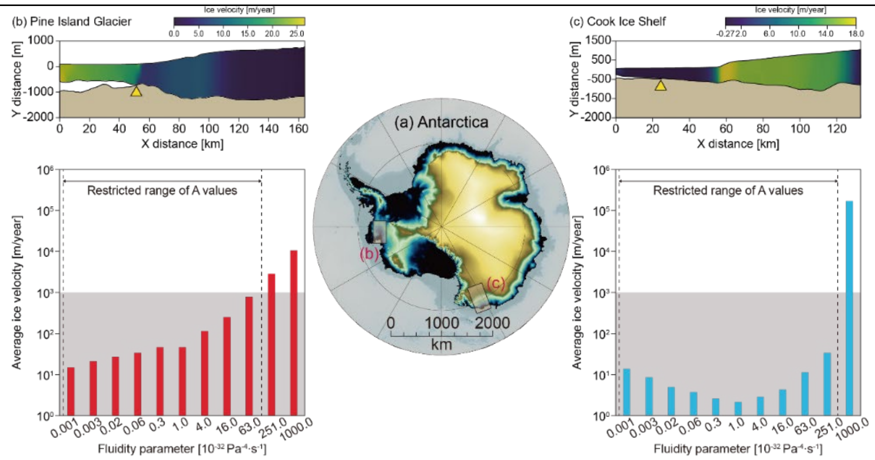
We appreciate Reviewer #1's concern about the possibility of over-restricting the range of A values. We also recognise that our results should be applicable to a wider region of Antarctica. Furthermore, our result should not be restricted to the limited cases of specific ice shelves. To address the concerns of Reviewer #1, we have performed additional analyses to address the limitations of our approach for determining the range of A values, specifically, 4.0 to $16 \times 10^{-32}\ \mathrm{Pa^{-4}s^{-1}}$. To address the concerns of Reviewer #1, we have extended our study to include additional numerical experiments on two other Antarctic ice shelves, the Cook Ice Shelf and Pine Island Glacier. These two ice shelves were chosen because of their different physical parameters (e.g., bed topography, surface elevation, ice thickness, and shelf length) and ice deformation.



Revised Figure 1.

Antarctic bed topography models with Cook Ice Shelf and Pine Island Glacier

The figures below show the numerical results for Cook Ice Shelf and Pine Island Glacier. The experiments were performed with the same range of A values (10^{-35} to 10^{-29} $\mathrm{Pa}^{-4}\mathrm{s}^{-1}$), as used in the original manuscript. We found that the Pine and Cook glaciers yielded ice flow velocities corresponding to the average Antarctic ice velocities (see the grey shaded zone in the figures below) in the A value range of 10^{-35} to 63.0×10^{-32} $\mathrm{Pa}^{-4}\mathrm{s}^{-1}$ and 10^{-35} to 251.0×10^{-32} $\mathrm{Pa}^{-4}\mathrm{s}^{-1}$, respectively. The final range of A values, including Cook Ice Shelf and Pine Island Glacier, is the same as the range of A values presented in this study.



Variation of ice flow velocity with A-values on the Cook Ice Shelf and Pine Island Glacier

The Shackelton Ice shelf in particular is an outlier in terms of the appropriate range of A values. It would be useful to explore in the discussion what the suggested range of A values would be without this case and have some statistical analysis and a final summarizing figure showing the suggested A values for each case examined.

Authors' reply:

We appreciate the reviewer's insightful feedback and suggestions on the A value analyses, particularly for the Shackleton Ice Shelf, which has extremely slow ice flow compared to the other ice shelves. In this revision, we report two different ranges of A values from the model sets: one including the Shackleton Ice Shelf and one excluding it. The comparison suggested that removing the Shackleton Ice Shelf from the model set would increase the range of A values. When the Shackleton was included (as in the original manuscript), the range of A values was 4.0 × to 16.0 × 10^{-32} $\mathrm{Pa}^{-4}\mathrm{s}^{-1}$ (an order of one). However, when the Shackleton was removed (for the revised manuscript), the range of A was extended, from 0.06 × to 16.0 × 10^{-32} $\mathrm{Pa}^{-4}\mathrm{s}^{-1}$ (an order of three). We also confirmed that including additional Antarctic ice shelves (i.e., Cook Ice Shelf and Pine Island Glacier) to this analysis resulted in the same range (i.e., 4.0 × to 16.0 × 10^{-32} $\mathrm{Pa}^{-4}\mathrm{s}^{-1}$) as in the original manuscript. We believe that this additional experiment provides a stronger generalisation for this range of A values.

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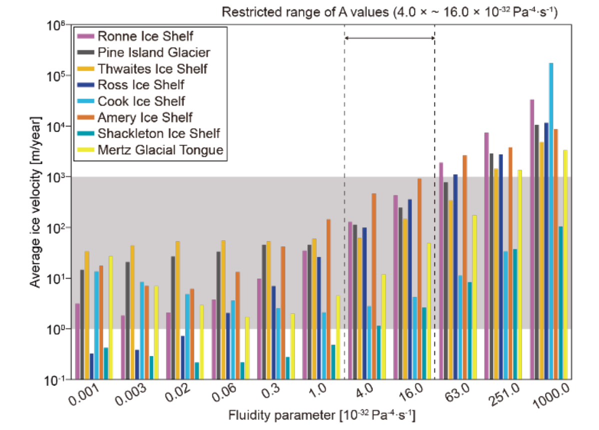
<td>
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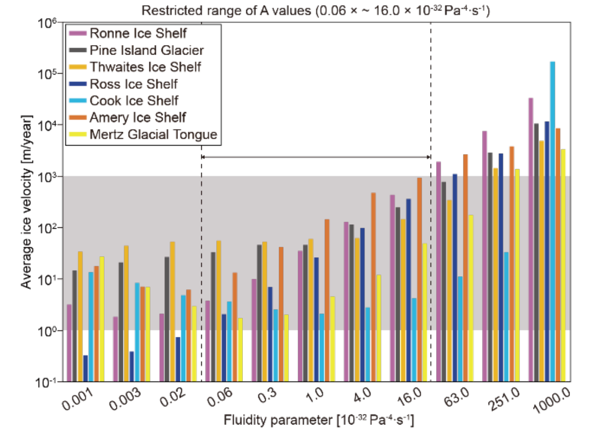
<td>
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<td>Includes all ice shelves (in the original draft)</td>
<td>Excludes the Shackleton Ice Shelf, and adds the Cook Ice Shelf and Pine Island Glacier</td>
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We admit that the A values derived from including the Shackleton Ice Shelf further narrow the range of A values. As stated above, the model set without the Shackleton resulted in an increased range of A values (an order of three). Although the order of the A value range is increased from one to three, an order of three is still meaningful. Typically, for n = 3, the range of A values used in modelling ice sheet dynamics has an order of three (Millstein et al., 2022).

However, we want to recall that the aim of our study was to improve the understanding of the complex rheological behaviour when n = 4. To limit the range of A values in order to minimise the errors in the numerical simulations caused by the large range of A values, using both idealised and Antarctic bed topography models, which are widely used in ice sheet dynamics in general.

Although we seriously considered removing the Shackleton results from the manuscript because Shackleton can be considered as an outlier, we ultimately decided in the end to report "an order of one" so that the A values would have a wider application across the Antarctic shelves, in line with the aims of our study.

We have also noted in the Discussion section that in the absence of the Shackleton, the A value range is of the order of three. Furthermore, we emphasised that this order of three (i.e., 0.06 × to 16.0 × 10^{-32} $\mathrm{Pa}^{-4}\mathrm{s}^{-1}$) is significantly narrower than the experimentally obtained A value range, which is an order of six (10^{-35} to 10^{-29} $\mathrm{Pa}^{-4}\mathrm{s}^{-1}$).

There is also likely sufficient unaccounted for physics implicit in A, such as temperature variation, fabric induced anisotropy, grain size etc. which would give an order of magnitude variation at least in the true value. This should also be mentioned in the discussion.

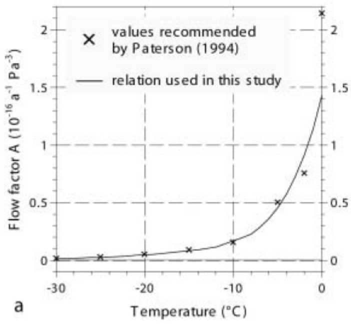
Authors' reply:

We very much appreciate the reviewer's comment about mechanics, which may not have been considered when setting the A value range in our study. Indeed, factors such as temperature change, fabric-induced anisotropy, and grain size are indeed very important in controlling ice viscosity (Gillet-Chaulet et al., 2006; Hruby et al., 2020; Adams et al., 2021). We admit that in our original manuscript we didn't sufficiently discuss the complicated interaction of different physical factors on the A value. In this response letter, we have briefly reviewed the literature to date on the effects of temperature variation, fabric-induced anisotropy, grain size, damage, and water content on the mechanical properties of ice, which in turn affect the flow dynamics of ice.

Review of possible factors affecting A values

1) The effect of temperature on the A value

The influence of temperature on the A value in Glen's law, which is the prefactor to the n^{th} power of the deviatoric stress, is a critical aspect of understanding glacier dynamics. Viscosity, in turn, determines the resistance of the ice to deformation, a key factor in glacier flow and creep. Warmer and less viscous ice can exhibit a more fluid-like behaviour compared to that of colder and more rigid ice. The temperature dependence of ice flow can be quantified by a change in the A value. A glaciology textbook by Cuffey and Paterson (2010) summarised the exponential relationship between temperature and the A value, highlighting the profound sensitivity of ice to temperature variations. Even within a narrow temperature range (-10°C to 0°C), the variation in the A value is large. The figure below is a plot of the temperature dependence of A from Jasen et al., 2005. A has relatively low values when the ice temperature is low. This means that colder ice is more difficult to flow. In particular, it can be seen that the value of A increases rapidly as the temperature rises near the melting point of the ice.



Model experiments on large tabular iceberg evolution: ablation and strain thinning (Jansen et al., 2005)

Typically, the A value is parameterised with an activation energy for ice creep, which quantifies the energy required to initiate deformation. The exponential increase in the A value with temperature reflects the decrease in the effective energy barrier to ice deformation, allowing more pronounced flow as temperatures approach the melting point.

2) The effect of ice fabric and grain size on the A value

The intricate relationship between crystal orientation, texture, and flow dynamics is a subject of great interest in glaciology. Ice-crystal fabric (Lilien et al., 2021) refers to the orientation and arrangement of ice crystals in glaciers, which plays an important role in the internal flow and deformation processes of glaciers. Ice-crystal fabric provides clues to how glaciers move and deform by describing how ice crystals are arranged according to the direction of glacier movement. The role of fabric in determining the A value is also significant, although it is difficult to quantify due to its dependence on specific fabric types, as well as the deformation history of the ice (Hudleston et al., 2015). Azuma (1994) suggests that the presence of a strong single maximum fabric can increase the deformation rate compared to isotropic ice under similar stress regimes. Strongly aligned crystal fabrics promote deformation by facilitating sliding along specific crystal planes, thereby increasing A. However, the effect of fabrics on glacier flow is complex, depending on both the deformation history and temperature conditions (Wilson and Peternell, 2012). This complexity suggests that the glaciers with similar climatic temperatures and different flow histories may exhibit different flow behaviour. Previous studies of ice deformation experiments (Goldsby and Kohlstedt et al., 2001; Behn et al., 2021) showed that grain size has a significant effect on strain rate, with strain rate increasing as grain size decreases. The quantitative relationship between grain size and the A value has been investigated in several studies.

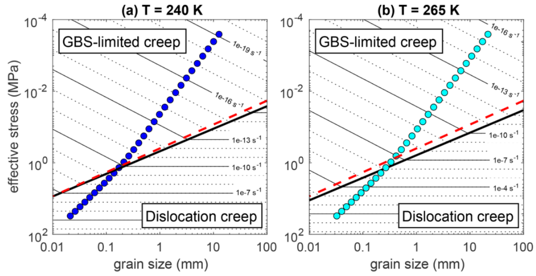
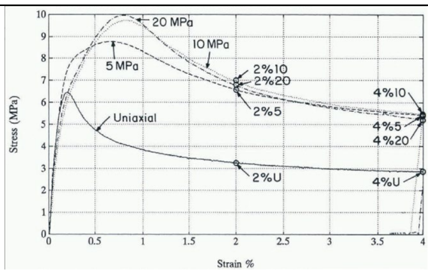


Figure 3. Effective stress vs. grain size at **(a)** 240 K and **(b)** 265 K calculated for a shear zone of fixed width using the wattmeter. Dark and light blue symbols correspond to the steady-state grain size predicted from a single model simulation at a given strain rate. Dashed red lines show location of the piezometer (Jacka and Li, 1994). Model results are overlain on a deformation mechanism map for ice calculated at the appropriate temperature using the flow law parameters from Goldsby and Kohlstedt (2001). Background contours correspond to strain rate; the thick black line indicates the boundary between GBS-limited creep (upper left) and dislocation creep (lower right). Under these conditions the location of the field boundary and piezometer are very similar.

The role of grain size evolution in the rheology of ice: implications for reconciling laboratory creep data and the Glen flow law (Behn et al., 2021)

3) The effect of damage on the A value

The concept of damage in ice sheet dynamics refers to the presence of structural irregularities (or weaknesses), such as cracks and microdefects, which significantly affect the strength of the ice (Duddu and Waisman, 2012). These imperfections in the ice matrix act as focal points for strain concentration, facilitating deformation at relatively low applied stresses, compared to undamaged ice. From a physical perspective, the damaged zones within the ice matrix can act as conduits for deformation, allowing the ice to adapt and flow even under relatively low stress conditions (Stone et al., 1997). It would therefore be expected that ice with a high degree of damage would have a higher A value. The relationship between damage and the A value highlights the importance of considering structural integrity and damage mechanisms when modelling glacier flow. For example, the presence of extensive crevasse or frost damage can alter local flow dynamics, as well as the overall stability and evolution of the glacier system.



Experiments on the damage process in ice under compressive states of stress (Stone et al., 1997)

4) The effect of water content on the A value

The water content of glacier ice is a key factor that significantly influences the dynamics of ice flow, primarily through its effect on the internal friction of the ice (Brown et al., 2017; Adams et al., 2021). The presence of water in a glacier lubricates the space between ice crystals, reducing the overall viscosity of the ice mass.

The effect of water on glacier flow can be particularly noticeable at the base of a glacier. Basal sliding, the process by which a glacier slides over its bed, is greatly enhanced in the presence of water. This lubricating effect accelerates glacier movement, which adds to the complexity of predicting glacier dynamics due to the non-linear response of flow rates to changes in water content. Adams et al. (2021) argued that, below a water content threshold of 0.6%, ice viscosity decreases significantly with increasing water content. However, above the 0.6% threshold, the viscosity dependence on water content becomes negligible, with the viscosity remaining almost constant. This implies a transition in the ice creep mechanism that depends on the water contents. Thus, the relationship between water content and A value should be parameterised.

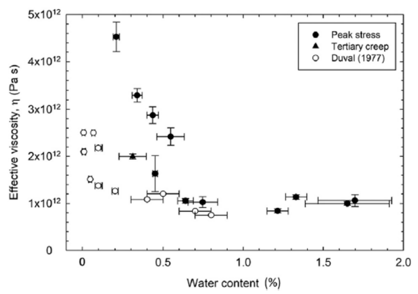


FIGURE 6 | Effective ice viscosity as a function of water content, as measured in the 11 experiments to peak stresses and one tertiary-creep experiment of this study, compared with the tertiary-creep results of Duval (1977). Duval's rotary experiments were conducted at a constant shear stress of 0.29 MPa.

Softening of temperate ice by interstitial water (Adams et al., 2021)

Ice rheological parameters, such as A value, are difficult to predict accurately in environments with multiple interrelated factors (e.g. water content, temperature, ice fabric, grain size, and damage). In our study, we attempted to quantify the effect of the A value, which is highly dependent on environmental factors, especially temperature. Many previous studies have assumed a constant value of A (over space and time) for numerical simulations without considering other environmental factors (Favier et al., 2012), especially for simulations with n = 3.

Following the efforts of previous studies to isolate the effect of A value on ice dynamics, we have restricted the wide range of constant A values to a narrower range at n = 4. However, we fully acknowledge the need to consider the spatially and temporally variable distribution of A values. We have added a new discussion of various factors affecting A values, including water content, temperature, grain size and damage, in the Discussion section, with relevant references, as reviewed above.

In the Discussion section,

Millstein et al. (2022) showed that a value of n = 4.1 ± 0.4 better approximates viscous ice flow than the commonly used n = 3 in fast-flowing and highly stressed ice shelves (e.g., Ronne and Ross Ice Shelf). Higher values of n increase the sensitivity of viscosity to changes in stress and temperature, which can lead to significant variations in numerical simulations. Therefore, when calculating ice flow velocity with n = 4, sensitivity analysis of other parameters in Glen's law, such as the A value. We have performed numerical simulations using the fluidity parameter (A) as a constant value in ice dynamics models. However, the various physical factors (e.g. temperature, ice crystal fabric, and ice grain size) affect the value of the fluidity parameter. The fluidity parameter (A) is influenced by temperature, ice structure, grain size, damage and moisture content, which in turn affect ice flow dynamics. Cuffey and Paterson (2010) suggested that temperature changes in the range -10 °C to 0 °C have a significant effect on the A value, by influencing the viscosity and deformability of the ice. Furthermore, ice crystal fabric and grain size can determine the response of the glacier to applied stresses (Goldsby and Kohlstedt et al., 2001). Structural damage within the glacier, such as cracks and microdefects, can significantly reduce deformation resistance, enhancing glacier flow (Duddu and Waisman, 2012). The water content of the glacier ice also acts as a lubricant, reducing internal friction and increasing flow, particularly promoting basal sliding. However, accurate prediction of ice rheology parameters is challenging due to multiple interrelated factors such as water, temperature, ice fabric, particle size, and damage. Based on the narrow range of A values refined in this study, we expect to derive A values that more accurately represent the behaviour such as ice temperature and ice velocity variations.

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In ice sheet dynamics modelling, the inversion method has been widely used to derive spatially and temporally variable rheological and frictional parameters, as highlighted in previous studies (Choi et al., 2023; Wolovick et al., 2023). In addition to improving the ability of models to fit observed ice velocities, such methods ultimately enhance the predictive capability of future ice behaviour. However, we focused on the use of a constant value of A with a stress exponent (n) of 4. The constant value of A provides a baseline value for the sensitivity of ice flow to rheological changes. The narrowed range of A values in our study was achieved by minimising the error between the numerical model and observed Antarctic ice velocity, allowing the range of A values to be used as initial values of temperature-dependent ice viscosity. We expect that this approach will provide insights for the development of refined model parameters.

Significance: The paper will be useful to ice sheet modellers in general, and hopefully encourage more studies using n=4.

Presentation quality: The paper is generally well written and concise. The title provides a clear summary of the work, and the abstract communicates the main results, though I think it should be noted in the abstract that this is a 2D study.

Authors' reply:

We are grateful for the reviewer's kind description of the title and abstract of our manuscript. We recognised the importance of explicitly mentioning the (two) dimensionality of the study. We have revised the abstract to state that the analysis was performed in a two-dimensional context. This change ensures that readers are immediately informed of the scope and methodological framework of our analysis, thereby avoiding any potential misunderstanding of the dimensionality of the study.

In the Abstract section,

⋯Here, we refined A to within one order, aligning with observed Antarctic ice velocities with two-dimensional simplified slope and Antarctic bed topography models. ⋯

Specific Comments

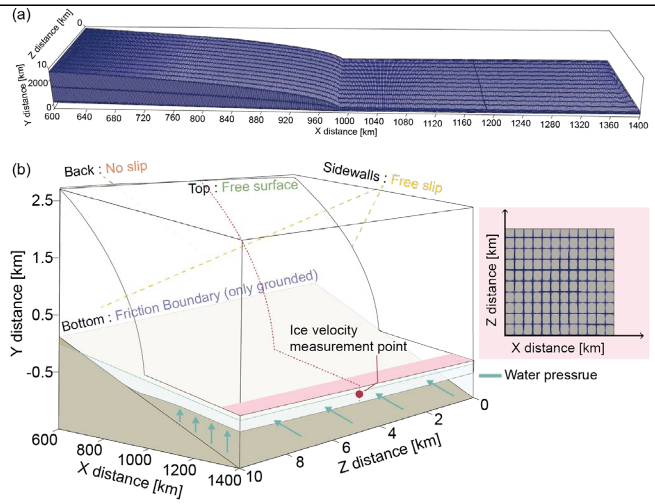
- *I would like to see at least one 3D simulation alongside the 2D cases for the idealised configuration explored here, to ensure that the same range of A values are found in 2D and the 3D cases. The limitation of 2 dimensions and how things may change in 3D should also be included in the discussion.*

Authors' reply:

We appreciate the reviewer's insightful suggestion to include the 3D simulation for the idealised models in our study. We have discussed the limitations of the 2D simulations and possible changes in the 3D simulation based on additional idealised 3D models.

Although two-dimensional (2D) models are useful for investigating plane-strain problems (very large in-plane width with low computational cost), 2D simulations only consider vertical and horizontal stresses. The 2D model has inherent limitations, particularly when modelling the complex dynamics of large glaciers or ice sheets, especially around the grounding line position, which is sensitive to stress changes in three-dimensional directions. Stress interaction in the in-plane direction can be important for the stability of ice sheet mechanisms. Although three-dimensional (3D) modelling leads to a significant increase in computational effort (in terms of cost and coding), 3D models can more accurately reflect the complex internal structure and dynamics of the entire ice sheet. In particular, changes in bed topography and ice flow along the in-plane width can have a significant effect on the behaviour of the ice sheet. These changes can be better captured in a three-dimensional model. In addition, detailed changes in stress distribution, including the interaction of lateral and vertical stresses, can be captured in the 3D model, which can have a dominant effect on the response of the ice sheet to different conditions. Through simple testing with an idealised 3D slope model, we can improve the predictive capability of our model for ice sheet response, which can ensure detailed analyses of ice strength.

We constructed an idealised 3D slope model to address the reviewer's concerns. The bottom (frictional boundary condition), top (free surface), back (no slip) and front (water pressure) boundary conditions were the same as for the 2D model. The sidewalls required for the 3D model were set to free slip, following Favier et al. (2012). To minimise the effect of the sidewalls on the boundary conditions, the ice velocity was measured at the center of the width (i.e. 5 km) (see the red dot in the figure below). To reduce the computational cost of 3D modelling, we developed a 3D model 8000 km long and 10 km wide around the initial grounding line. The mesh size along the Z axis is kept the same as in the 2D models (i.e., 0.9 km). Please note that the mesh-size in the in-plane direction (Z axis) is very large (i.e., 1 km) to save computational cost. However, the time-step size (0.01 year) of the 2D model is maintained in the 3D model.



Model setup in 3D idealised slope model

The modelling results are shown below:

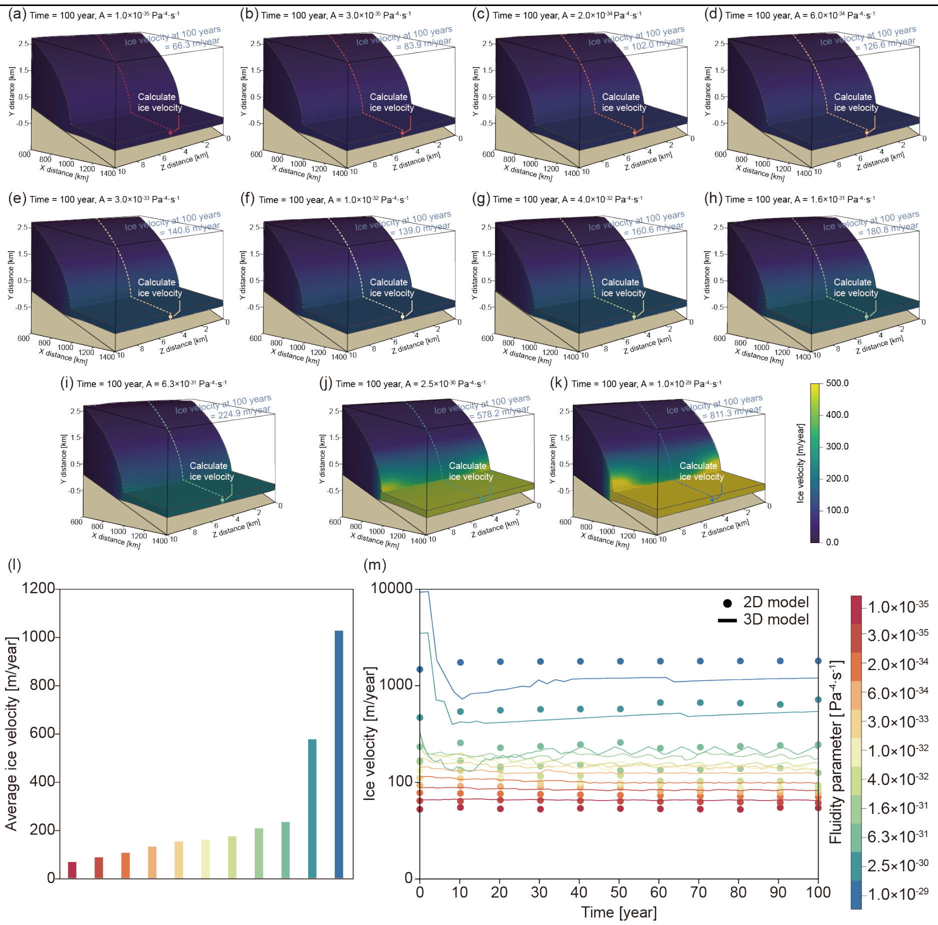


Fig. S6 in the revised manuscript

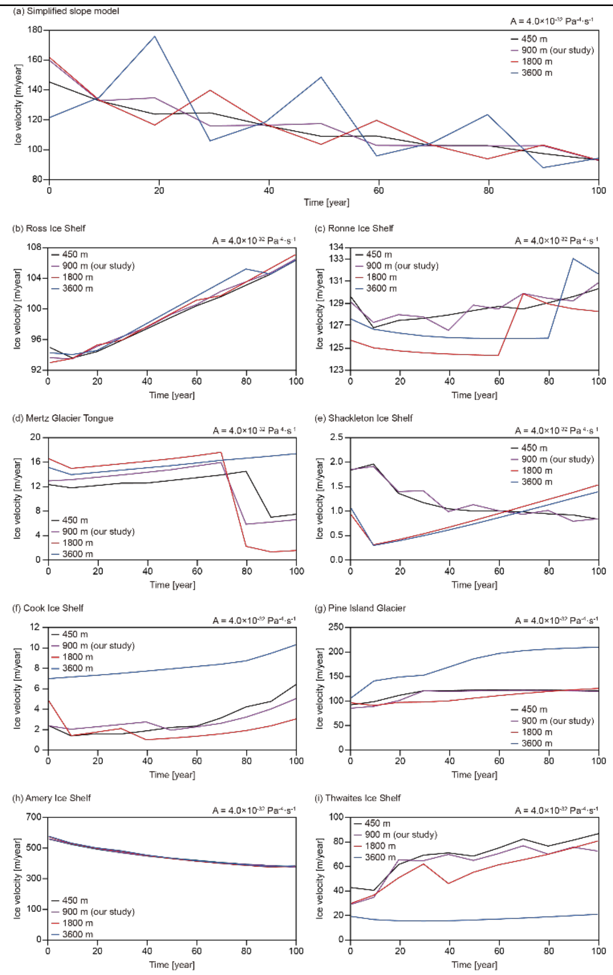
Figures a-k show the ice velocity distribution at time = 100 years for A values ranging from 10^{-35} to 10^{-29} $Pa^{-4}s^{-1}$. We found that the overall velocity changes are very similar according to the A values (Figure m). The range of constrained A values was also derived as 10^{-35} to 2.5×10^{-30} $Pa^{-4}s^{-1}$, as in the 2D model.

There should be a demonstration of the mesh independence of the results, especially considering the saw-tooth oscillations in Fig 2., for both the idealized and realistic cases. This can just be included as a supplementary figure.

Authors' reply:

Following the reviewer's suggestion, we have included the mesh size test (i.e., resolution test) in the Supplementary Material of the revised manuscript. We believe that the resolution test is a critical for assessing the effect of the mesh size on the overall results of our study. In particular, minimising the effect of mesh size is important for determining the range of A values, which is the main objective of our study.

Therefore, we tested three different mesh sizes, *i*) the mesh size used in the original draft (900 m), *ii*) a half of the original mesh size (450 m), *iii*) a double of the original mesh size (1800 m), and *iv*) a quadruple the original mesh size (3600 m). Although the resolution tests were performed for all models (including the idealised slope and Antarctic bed topography models) and all A values, we have included the nine cases (i.e., Ross, Ronne, Cook, Thwaites, Amery, Shackleton Ice Shelf, Mertz Glacier Tongue, Pine Island Glacier and the idealised slope case) with A = 4.0×10^{-32} $\mathrm{Pa^{-4}s^{-1}}$ in the Supplementary Material. Please see the figures below.



The resolution tests with different mesh sizes showed that the velocities at 100 years are similar as the mesh size decreases. For example, in the idealised slope model (see figure a above), the resolution tests with all mesh sizes of 450 m, 900 m, 1800 m and 3600 m gave velocities of 93 m/year. A similar trend was found for the Antarctic bed topography models (see figures b-i).

For most Antarctic ice shelves, the 3600 m mesh size models have a significantly different ice velocity at 100 years compared to the 900 m mesh size models. However, the 450 m mesh size models show similar ice velocities to the 900 m mesh size models. For example, the ice velocity of the Rone Ice Shelf is similar for the 900 m and 450 m mesh sizes. For Pine Island Glacier, the velocity is 210 m for the 3600 m mesh size. However, the ice velocities of all other models in 1800, 900 and 450 m mesh sizes converge to 120 m/year. Ice velocities tend to be similar at mesh sizes of ~900 m. This mesh independence of velocity confirms the suitability of the 900 m mesh size chosen for our study.

For the idealised models, we found that an increase in mesh size correlated with longer oscillation periods of velocities and grounding line position. This indicates that the influence of the mesh size on the grounding line motion in the idealised slope model is significant. The occurrence of this oscillation across all mesh sizes confirms that the physical motion is independent of mesh size. In the original draft, we had already discussed that the oscillations were due to the discrete nature of the grounding line position definition. To quote a sentence from the original manuscript:

In the Results section of the original manuscript,
The oscillation in ice velocity in Figure 2a is caused by the interaction with the discrete variations in the position of the grounding line, which is determined by the mesh size. As the grounding line advances, the ice velocity decreases rapidly due to the increase in frictional stress. This dynamics leads to oscillations in the overall ice velocity (see Fig. S2 in the Supporting Information).

The oscillations were not pronounced for mesh sizes of 450 m, 900 m, 1800 m, and 3600 m. For the Antarctic bed topography model, the oscillation behaviour with the mesh size showed a distinct pattern compared to the idealised slope model. In particular, the oscillations were not pronounced for mesh sizes of 450 m, 900 m and 1800 m. This discrepancy can be attributed to the complex bed topography and lower surface interface (e.g., tills and cavities) in a realistic setting. In addition, the complex bed topography of Antarctica results in a more gradual movement of the grounding line, as opposed to the abrupt changes in the idealised slope model. However, when the mesh size was too large (e.g., 3600 m), oscillations in the position and velocity of the grounding line occurred, highlighting the importance of selecting a sufficiently small mesh size.

The definition in Eq. 6 and your values of m = 3,5,7,9 later are inconsistent: with these m values Eq. 6 should read 1/m not m.

Authors' reply:

We greatly appreciate the reviewer's careful review of our manuscript, especially the inconsistency between Equation 6 and the chosen values of m. We have thoroughly checked the formulae and parameters for the Weertman friction law using the relevant literature. Please refer to the box below.

motion which is referred to as basal drag. Weertman (1957) demonstrated that in such a case the relation between τ_b and u_b takes the form of a power law:

$$\tau_b = C_W u_b^m, \quad (1)$$

where C_W is a friction parameter, hereafter called Weertman friction parameter, and m a positive constant. This is the most

Contour plots of τ_b given in the plane (N, u_b) are represented in Fig. 1 for the four friction laws (Eqns (1)–(4)) using $m = 1/3$, $q = 1$, $C_W = C_B = C_S = 7.624 \times 10^6$ S.I. and $f = C_{max} = 0.5$; with this choice the four laws give the same τ_b for the value $N = 1$ MPa (highlighted by the black vertical dashed lines in Figs 1a–d). By definition, τ_b is independent

Brondex et al., 2017

We acknowledge that the correct presentation does indeed require expressing m as 1/m in order to align our study with the established theoretical and empirical frameworks documented in the literature. This correction is particularly important given the influential contributions of Brondex et al. (2017), Barnes and Gudmundsson (2022) to our understanding of the Weertman friction law. We have revised Equation 6 in our manuscript with 1/m to ensure that our approach is consistent with both of our data set for m = 3, 5, 7, and 9. We sincerely appreciate the reviewer's guidance in identifying this critical error.

Table 1. Values and Descriptions of parameters

Description	Symbols	Values [unit] and equations
⋮	⋮	⋮
Fluidity parameter	A	10^{-35} to 10^{-29} $[\mathrm{Pa}^{-4} \cdot \mathrm{s}^{-1}]$
Friction coefficient	C_w	7.624×10^6 $[\mathrm{Pa} \cdot \mathrm{m}^{-1/3} \cdot \mathrm{s}^{1/3}]$
Sliding exponent	m	~~3, 5, 7, and 9 [-]~~1/3, 1/5, 1/7, and 1/9 [-]
⋮	⋮	⋮

Technical Comments

Line 30-31: By incorporating geodetic creep data… I'm not sure what is meant precisely by this phrase. Furthermore, while the Cuffy and Behn do support n=3, it would be relevant to say here that n=3 has been used since Glen's classic experiments (Glen, 1952).

Authors' reply:

We thank the reviewer for clarifying the phrase "incorporation of geodetic creep data" in our manuscript. We are referring to the integration of measurements from different geodetic techniques, such as InSAR, with numerical modelling. By integrating geodetic creep data with ice sheet modelling, this method can provide insight into ice flow velocity and deformation, which is essential for improving the accuracy and reliability of the ice sheet model.

In the Introduction section,

~~By incorporating geodetic ice creep data (Cuffey and Kavanaugh, 2011; Behn et al., 2021), ice sheet modeling has suggested an n value of approximately three, which effectively reproduces the surface ice velocity in Antarctica (Martin and Sanderson, 1980; Pattyn et al, 2012), such as the Amery Ice Shelf (Thomas, 1973; Hamley et al., 1985).~~

Glen's experiments contributed significantly to the understanding of ice deformation, revealed the complex relationship between stress and strain rate (Glen, 1952; Glen, 1958). In ice sheet modelling, the value of n of approximately 3 has been used, which effectively reproduces surface ice velocities in Antarctica (Martin and Sanderson, 1980; Pattyn et al., 2012), such as the Amery Ice Shelf (Thomas, 1973; Hamley et al., 1985).

Throughout the manuscript mathematical variables in the text should be written in math mode, i.e. A and $n = 4$ rather than A and n=4.

Authors' reply:

We have carefully revised the document to ensure that all mathematical variables are formatted in LaTeX math mode (e.g., A and $n = 4$) for the readability of the manuscript. This correction has been applied throughout the manuscript. Please let us show the reviewer the examples of the correction.

In the Abstract section,
…The suggested range of the fluidity parameter (~~A~~ A) for ~~n = 4~~$n = 4$ is of the order of six (i.e., 10^{-35} to 10^{-29} $\mathrm{Pa^{-4}s^{-1}}$), leading to a significant uncertainty in ice velocity than when ~~n = 3~~$n = 3$.
In Introduction section,
…The value of ~~A~~ A derived from a laboratory ice deformation experiment with ~~n = 3~~$n = 3$ ranged from 1.8 to 93×10^{-25} $\mathrm{Pa^{-3}s^{-1}}$ (MacAyeal et al., 1998),
In Method section,
…when ~~n = 4~~ $n = 4$, comparing ice flow velocity over a total period of 100 years.

In Results section,

⋯fluidity parameter (~~A~~ A) when ~~n = 4~~ $n = 4$ (power-law stress exponent).

In the Discussion section,

instead of ~~n = 3~~ $n = 3$, better explains ice flow in Antarctica (e.g., Behn et al., 2021; Ranganathan et al., 2021).

In the Conclusions section,

⋯on ice flow velocity, with ~~n = 4~~ $n = 4$⋯

Line 85: should be lowercase p for pressure

Authors' reply:

We thank the reviewer for bringing this error to our attention and apologise for any confusion it may have caused.

In the Method section,

η, ρ_i, **g**, and ~~P~~ p indicate the ice viscosity, ice density, gravitational acceleration, and pressure, respectively.

Around Eq. 4 and 5 ε_e should be defined or the table should be referenced

Authors' reply:

In response to this comment, we have added a reference to the Table 1, where the effective strain rate ($\dot{\varepsilon}_e$) is defined. Specifically, we have placed the sentence near equations 4 and 5, directing the readers to Table 1 for the definition of $\dot{\varepsilon}_e$.

In the Method section,

⋯Glen's Law (Eq. 5) determines the viscosity as a function of A value and the power of the effective strain rate $\dot{\varepsilon}_e$ (see Table 1), representing the magnitude of the strain rate tensor.

$$\eta = 2^{-1}A^{-1/n}\dot{\varepsilon}_e^{(1-n)/n} \quad (5)$$

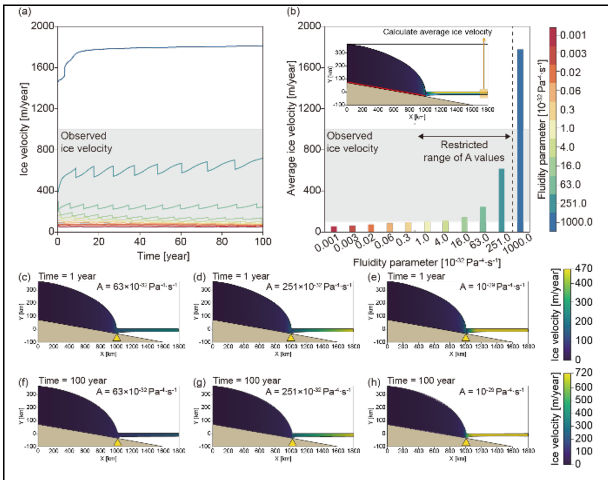
Tabel 1

Strain rate	$\dot{\varepsilon}_{xx}$, $\dot{\varepsilon}_{yy}$	[1/s]
In-plane strain rate	$\dot{\varepsilon}_{zz}$	$-(\dot{\varepsilon}_{xx} + \dot{\varepsilon}_{yy})$ [1/s]
Effective strain rate	$\dot{\varepsilon}_e$	$\left(0.5(\dot{\varepsilon}_{xx}^2 + 2\dot{\varepsilon}_{xy}^2 + \dot{\varepsilon}_{yy}^2 + \dot{\varepsilon}_{zz}^2)\right)^{0.5}$ [1/s]

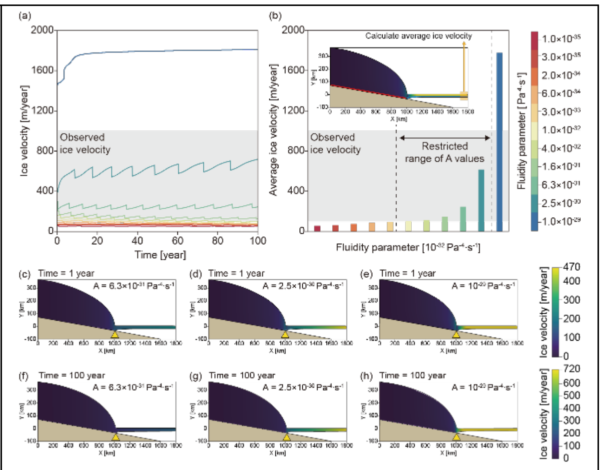
The range of Fluidity parameters in Fig 2 should be expressed in exponent notation (i.e. 10^-29 rather than 0.001 x 10^-32)

Authors' reply:

Regarding the reviewer's comments on the presentation of the range of A values in Figure 2, we appreciate the suggestion to change the exponential notation for accuracy. The recommendation to present these values in a more standardised form, such as 10^{-29} rather than $0.001 \times 10^{-32} \mathrm{Pa}^{-4} \mathrm{s}^{-1}$, will be incorporated in the revised manuscript. An excerpt of the manuscript and figure with the change in exponential notation is shown below.



Original Figure 2

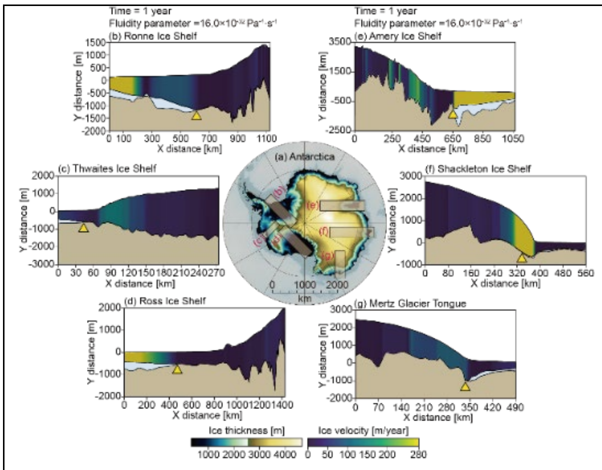


Revised Figure 2.

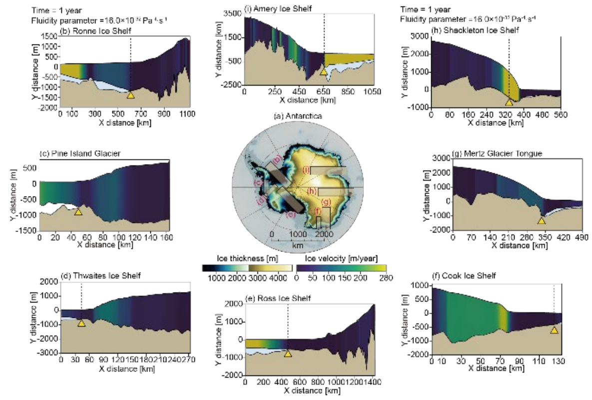
Line 150 of the text references dotted lines showing the positing of BedMap2 grounding lines in Fig 3, yet I cannot see them in this figure.

Authors' reply:

We appreciate the reviewer's attention to detail in evaluating our manuscript. We acknowledge the confusion caused by the absence of a dotted line to indicate the location of the BedMap2 grounding line in Figure 3. To rectify this, we have revised Figure 3 to ensure that the dotted lines clearly represent the BedMap2 grounding lines as originally intended.



Original Figure 3.



Revised Figure 3.

We thank Reviewer once again for the valuable time and consideration.

Sincerely,

Sujeong Lim and Prof. Byung-Dal So

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