Response to reviewer 2 (Elise Kazmierczak)

M. Haseloff, I. J. Hewitt, R. F. Katz

May 19, 2025

We thank the reviewer for their thoughtful and constructive review. In this document, reviewer text is in black and our response to it is in blue. Manuscript text is in italics, with original text in black and changes in red.

The paper is well-written and demonstrates a high level of scientific quality. The topic is of significant interest and aligns well with current research on the influence of subglacial hydrology on ice motion, particularly within the context of the Antarctic ice sheet. This area of study has gained renewed attention in recent years, addressing gaps in the existing literature.

The research demonstrates the impact of subglacial hydrology on marine ice stream dynamics, coupling various systems in a positive feedback loop involving ice flow, basal heat dissipation, and basal lubrication. By using a simple flow-line model, the authors explore different subglacial phenomena arising from the presence of subglacial water in a soft bed system. Their results emphasize the dependence of ice stream dynamics on basal conditions.

I recommend the publication of this paper following a few minor revisions.

I have structured the comments into general comments and line-by-line comments. The general comments are suggestions to improve clarity for a new reader, curiosity questions, or suggestions of improvements that are recurrent throughout the paper.

1 General comments and suggestions

- I suggest to summarize in a simple and clear way the model at the beginning of the paper. Indeed, it is a bit complicated during the first read of the paper to understand well in terms of subglacial hydrology what is considered and what is not. For example, please specify that it's a model only applied on a soft bed and which encompasses inefficient and efficient subglacial drainage systems through a hydraulic conductivity factor that increases with decrease of the effective pressure. No switch between efficient and inefficient drainages is assumed, as well as no channels at higher subglacial water flux. Furthermore, no interaction between subglacial water and ocean water and no vertical infiltration are considered. I also think you could more explicitly summarize what subglacial processes the kappa factor encompass.

  In the introduction, we have expanded the paragraph describing our model as follows:

  The goal of this study is to investigate the simplest possible feedback between fast flow, heat dissipation, and basal lubrication, and its role in marine ice sheet dynamics. We use a model that includes the positive feedback between fast flow and basal lubrication through both storage of water in the subglacial sediment as well as evacuation of water through an active subglacial drainage system. Subglacial water flow is modelled with a Darcy-style flux law. The hydraulic conductivity is the quotient of a conductivity factor and the effective pressure, i.e., it is assumed to increase as the effective pressure decreases, as is common for distributed systems. The overall balance of storage and subglacial discharge ~~these two processes~~ is determined by the hydraulic conductivity factor ~~of the bed~~. At very low hydraulic conductivity, the model reproduces the undrained bed model, and water content of the bed is determined by the local energy balance. At very high hydraulic conductivities, hydraulic gradients cannot develop at the bed; in this limit the effective pressure at the bed is set by the ice and bed geometry alone, independent of the local melt rate.

In the discussion, we added to section 4.4 on model limitation:

We also ignore the role of ice shelves here. Buttressing ice shelves can alter marine ice stream dynamics (Gudmundsson et al., 2012; Gudmundsson, 2013; Haseloff and Sergienko, 2018, 2022). In addition, at the grounding line, subglacial hydrology can interact with the ocean in multiple ways not taken into account here, for example through seawater infiltration and the initialisation of subshelf meltwater plumes which might alter ice shelf buttressing (e.g., Jenkins, 2011; Robel et al., 2022; Ehrenfeucht et al., 2024).

We have also changed section 4.3 to more explicitly state that we do not consider channelisation:

For high water discharge conditions, it is plausible that a transition from distributed to channelised drainage might occur (Walder and Fowler, 1994; Röthlisberger, 1972; Hager et al., 2022; Dow et al., 2022). Under these conditions, we expect the net discharge to increases with effective pressure, rather than decreases. ~~Such a scenario could occur in a highly channelised subglacial drainage system (Röthlisberger, 1972).~~ In Greenland, where abundant meltwater can drain to the bed, increasing channelisation leads to a strengthening of the bed at the end of the melt season (Schoof, 2010; Bartholomew et al., 2012). We ~~would~~ also expect the conductivity to vary locally, so that we interpret $K_{d,\mathit{eff}}$ as an effective hydraulic conductivity, averaged over spatial scales resolvable in ice sheet models.

- Also, I do not understand whether or not h_w & h_s are limited. That is the case, please mention it.

  The water content h_w can freely evolve, but values below 0 are unphysical; once the basal water content is zero, we need to solve for basal temperature, rather than water content. However, this scenario does not occur with our parameter choices. The thickness of the hydraulically-active, drained sediment layer h_s is bounded between 0 (fully frozen) and h_0 (completely unfrozen). To clarify this, we have made the following change:

  Note that the thickness of the unexpanded, hydraulically active sediment layer h_s is bounded between 0 (completely frozen) and h_0 (completely unfrozen). O~~o~~ur ~~modelling~~ parameter choices prevent the ~~entire~~ basal sediment ~~to freeze~~from freezing entirely ($h_w = h_s = 0$).

- Some values used in this research (e.g., constant coefficients in Table 1 or values of kappa used in experiments) are not referenced, and there is no explanation regarding the choice of their values. Please provide the references where applicable and add comments about the choices that had to be made.

  We added the following information to the table caption:

  Geometric (W, z_0, z_1), environmental (a, T_s, A, q_{geo}), and basal parameters (h_0, C) are chosen to be representative of Siple Coast ice streams and for comparability with previous studies (e.g., Robel et al., 2013, 2014; Tsai et al., 2015). Subglacial drainage parameters (e_r, e_c, N_r) are based on Tulaczyk et al. (2000).

- I think it's important to clearly specify that the processes you talk about are subglacial processes. Therefore, make sure to add the term "basal" with "melt" and "subglacial" with "water" when necessary. The same goes for the term "discharge" — make sure to specify whether it refers to water or ice.

  Done.

- In general, in the presentation of the results, I suggest emphasizing the quantitative values of the mentioned variations and referencing the relevant figures/videos more regularly.

  The manuscript has been edited for more consistent referencing and quantitative description, where appropriate .

- Does one of your limit cases could be interpreted as that of a hard bed system?

  While we focus on soft-bedded conditions, aspects of the results shown here extend to hard-bedded systems: Regularized Coulomb friction laws have been proposed for hard beds as well

(Helanow et al., 2020), and in the limit of high effective pressure, the basal shear stress reproduces a Weertman sliding law (Weertman, 1957). The main difference between hard- and soft bedded system might lie in the details of the subglacial drainage system, but if the flow is essentially Darcian with the hydraulic conductivity increasing with decreasing effective pressure, then qualitatively similar dynamics should be expected as long as no channelisation occurs. In this case melt would lead to an overall strengthening off the bed. In the manuscript, we acknowledge this in the discussion:

For high water discharge conditions, it is plausible that a transition from distributed to channelised drainage might occur (Walder and Fowler, 1994; Röthlisberger, 1972). Under these conditions, we expect the net discharge to increases with effective pressure, rather than decreases. ~~Such a scenario could occur in a highly channelised subglacial drainage system (Röthlisberger, 1972).~~ In Greenland, where abundant surface meltwater can drain to the bed, increasing channelisation leads to a strengthening of the bed at the end of the melt season (Schoof, 2010; Bartholomew et al., 2012).

- Have other geometries (slope/shape) of beds been investigated?

  Not systematically, as the goal of this study was to use the simplest possible model. Other studies have emphasized the importance of basal topography on marine ice stream dynamics (e.g., Sergienko and Wingham, 2021, 2024). Similarly, the use of a width-integrated model prevents the formation of lateral hydraulic gradients, which might be important for the observed patterning of the Siple Coast ice streams (Kyrke-Smith et al., 2014). Extension of this model to other geometries is a potential avenue for future work. We acknowledge these limitations in the discussion, where we write:

  Another limitation of the width-averaged approach is that it precludes the formation of ice ridges, whose surface slopes affect the ice stream stability by altering the hydraulic gradient (Kyrke-Smith et al., 2014).

- In terms of results, more details could be provided regarding the timing of the experiments. For example, I don't understand why, in Figure 2, there is a 800-year difference between d1 and d2, while in the other figures, the results are shown to take place over a scale of a few years. I also think a comment on the initial and final conditions would be interesting.

  The profiles in figure 2 were mainly intended for illustrative purposes, as they show the same information as figures 3 and 4. Times are relative to an initial point t_0 within the oscillation cycle shown in figures 4 (a: $t_0 = 6675$ yrs, b: $t_0 = 6300$ yrs, c: $t_0 = 6200$ yrs, d: $t_0 = 5800$ yrs); the displayed profiles are selected to illustrate the qualitative differences in ice stream behaviour. We will change the times to match the information in figure 4.

- What is the computation time for these models?

  Simulation times depend on the hydraulic conductivity parameter and of course model resolution. For $\kappa \lesssim 1$, and a grid spacing of $\Delta x = 100$ m, 10^4 model years are computed in about 24 hours on a single node. Simulations with $\kappa \gg 1$ require significantly more time (up to two weeks) due to limitations on the timestep. This information has been added to the description of the numerical model.

- In your text, you explain well that kappa is an average used to represent in 1D hydrological systems that would be found in 2D. You also mention that multiple systems can exist for N. However, depending on the drainage system, for the same flow, a different effective pressure could be obtained (cf. Fig. 4 Walder and Fowler, 1994). Maybe you discuss how your model could include other drainage systems.

  Figure 4 in Walder and Fowler (1994) shows effective pressure vs subglacial discharge of a mountain glacier-like scenario (large surface slope of $\sin \alpha = 0.1$) and an ice sheet-like scenario (small surface slope of $\sin \alpha = 0.001$), with a simplified version of the latter adopted in our study. While we are interested in the simplest possible model that can illustrate the role of subglacial hydrology and be used to identify the leading order controls (represented through κ) extension of our model to more sophisticated drainage models is an exciting research direction. For such an extension, explicitly resolving the across-flow direction becomes crucial and continuum-mechanical models capable of including such dynamics are beginning to emerge (e.g., Bueler and van Pelt, 2015; Sommers et al., 2018).

2 Line-by-line comments

2.1 Introduction

- L6: I don't understand why a hydraulically controlled motion is called a "surge", while a thermally controlled motion is referred to as an "oscillation". Shouldn't we use the same term, or are these two different phenomena?

  A comment also raised by the other reviewer. We will change surge to oscillations were appropriate.

- L25: Maybe add something that explains why existing observational work does not address the interplay between subglacial hydrology and marine ice-sheet dynamics, such as 'because of the lack of direct observation.'

  Done.

- L27: Maybe add: Gregov, T., Pattyn, F., & Arnst, M. (2023). Grounding-line flux conditions for marine ice-sheet systems under effective-pressure-dependent and hybrid friction laws. Journal of Fluid Mechanics, 975, A6.

  Done.

- L40: By reading this sentence, one might think that in an extreme case, this feedback loop never stops. Is it possible to add something to moderate it, like "up to a certain point"?

  We changed the sentence to:

  The dominant positive feedback mechanism then involves melting at the base of the ice; faster sliding leads to more heat dissipation, which in turn produces additional melt water that reduces basal drag and permits even faster sliding until other processes suppress further weakening of the bed.

- L44: add something like "Which is often the case because of the low porosity of this material"

  Done.

- L52: "subglacial water" –"and water content of the bed composed by till"

  We added the first part but we are opting to leave the second part of the sentence as is as the cited studies are not specific to till beds.

- L63: Give a numerical value for the low hydraulic conductivity

  Done: added ($K \ll 10^{-3}$ m s^{-1})

- L64: At what value of hydraulic conductivity is the limiting case obtained?

  Added ($K \gg 10^{-3}$ m s^{-1})

- L68: finite and intermediate hydraulic conductivities

  Changed finite to intermediate as suggested also by Reviewer 1.

2.2 The Model

- L76: It's not clear that the length refers to the domain and not to the flowline.

  Changed the sentence as follows:

  The computational domain is ~~a flow line~~ of length $L_x = 1000$ *km with a downward sloping bed at elevation* $b = z_0 - z_1 x$.

- L77: depth or thickness to clarify the word "content"

  Changed the sentence as follows:

  We solve for velocity u*, ice thickness* H*, water content of the bed* h_w *(given as water column thickness), and thickness of unexpanded, hydraulically active till layer* h_s*, which can evolve due to freezing and melting in the sediment, see figure 1.*

- L86-87: For n, keep "rheological" as used in the text or "viscosity" as in the table, but not both—avoid using two different terms. The value of epsilon is missing in the table. What is the value, unit, and source of epsilon? Also, please provide more details about Cw.

  We changed the description of n in the table and added the entry of ε. Regularisation of the viscosity term to avoid the viscosity to become infinite is common practice in ice sheet modelling (e.g., Schoof, 2006; Bueler and Brown, 2009). We have added the references. C_w arises in the width-integration of the ice flow equations. We have added a reference to Hindmarsh (2012) for further details.

- L88: Refer to some of these recent studies.

  Note that Zoet and Iverson (2020) is already referenced in the sentence. We have added Helanow et al. (2021) as reference for a hard bed.

- L92: Add a note that explains that since μ is constant at high effective pressure, you obtain a Weertman-style sliding law. Also, include a reference explaining why m = 1/3 is used.

  Note that we already write:
  For $\mu N \gg C|u|^m$ *this reproduces a Weertman-style sliding law* $\tau_b \sim C|u|^m$ *(Weertman, 1957), [...]*

  Because the exponent in the Weertman sliding law is related to the creep of ice, it is often set to $m = 1/n$ (Brondex et al., 2017; Weertman, 1974; Schoof, 2007b; Gudmundsson et al., 2012; Pattyn et al., 2012, 2013). We changed the sentence to:

  We use a regularized version of the slip law used in Tsai et al. (2015),

  $$\tau_b = \frac{C|u|^m \mu N}{C|u|^m + \mu N} \frac{u}{|u|}, \tag{1}$$

  with $m = 1/n$ *(e.g., Weertman, 1974; Pattyn et al., 2012; Brondex et al., 2017).*

- L99: Maybe add the reference: Shreve, R. L. (1972). Movement of water in glaciers. Journal of Glaciology, 11(62), 205-214.

  Done.

- L100: Maybe add references like van der Wel et al., 2013, Bougamont et al., 2014 and Bueler and van Pelt, 2015.

  van der Wel, N., Christoffersen, P., & Bougamont, M. (2013). The influence of subglacial hydrology on the flow of Kamb Ice Stream, West Antarctica. Journal of Geophysical Research: Earth Surface, 118(1), 97-110.

  Bougamont, M., Christoffersen, P., Hubbard, A. L., Fitzpatrick, A. A., Doyle, S. H., & Carter, S. P. (2014). Sensitive response of the Greenland Ice Sheet to surface melt drainage over a soft bed. Nature communications, 5(1), 5052.

Bueler, E., & van Pelt, W. (2015). Mass-conserving subglacial hydrology in the Parallel Ice Sheet Model version 0.6. Geoscientific Model Development, 8(6), 1613-1635.

Done.

- L100-L102: subglacial water

  Done.

- L103: If I understand correctly, the properties of the bed itself are not modified. I would suggest modifying the sentence to: "The conductivity only depends on the water content [...] and the properties of the bed are kept constant".

  Arguably, the effective pressure is a property of the bed, which changes in the model, as does the void space, which depends on the effective pressure. We have changed the sentence subtly thus:

  We assume that the hydraulic conductivity only depends on the water content of the bed, as is common for distributed systems (Hewitt, 2011).

- L109: The difference of pressures allows canals to deform the soft bed. So I will modify the sentence by "eroded and deformed".

  We have opted to leave the sentence as is, as the current formulation does not exclude the possibility of canal deformation, but avoids discussion of the contentious topic how much till beneath conduits actually deforms (see for example Damsgaard et al., 2017).

- L120: For the values of the model-specific constants, I suggest adding the sources of the values used.

  The following information has been added to the table caption:

  Geometric (W, z_0, z_1), environmental (a, T_s, A, q_{geo}), and basal parameters (h_0, C) are chosen to be representative of Siple Coast ice streams and for comparability with previous studies (e.g., Robel et al., 2013, 2014; Tsai et al., 2015). Subglacial drainage parameters (e_r, e_c, N_r) are based on Tulaczyk et al. (2000).

- L140: Add a reference for this.

  This is to be understood as a possible (logical) consequence of the model formulation, not a comment on observations. We have changed the sentence to clarify:

  ~~Theoretically,~~ It is conceivable that freezing could occur at smaller void ratios if subglacial drainage has removed water before the onset of freezing so that $N > N_c$.

- L14x: Add numbers/letters in Eq. 10 conditions for more clarity. I propose 10b.

  Since Eq. 10 is one equation, we reference the subcases with subscripts, e.g., $(10)_1$ etc. We have added explicit reference to the subcases to make the paragraph clearer.

- L153: Maybe add that the GL and the calving front are the same (even though it is mentioned on line 336).

  We have added the following sentence immediately after equation 12:

  In the numerical model, we assume that an unbuttressed ice shelf fills the domain from the grounding line to the domain boundary, where we apply $(12)_2$. This is mathematically equivalent to (12), which assumes that the ice sheet terminates at the grounding line (e.g., Schoof, 2007a).

2.3 Results

- L174: basal melt water

  Changed.

- L 175: In the limiting case of quasi-infinite conductivity of the hydraulic system, I do not understand how water can be evacuated without hydraulic gradients. From my understanding, this limit case corresponds to the height above buoyancy model. Could you provide me with further explanations?

  Indeed, the height above buoyancy model corresponds to assuming a quasi-infinite hydraulic permeability of the bed. Assume $\kappa \to \infty$, then equation (15) states:

  $$\frac{\partial \Phi}{\partial x} = -\frac{\mu N}{\kappa a L_x h_s} q_w \to 0 \quad \text{for} \quad \kappa \to \infty.$$

  However, this does not define the flux, which is now given through equation (4):

  $$\frac{\partial h_w}{\partial t} + \frac{\partial q_w}{\partial x} = m_b$$

  In steady state, this gives

  $$q_x(x) = \int_0^x m_b \, \mathrm{d}x$$

  Maybe more intuitive is to think of this as $\kappa \gg 1$. For large κ, infinitely small gradients in the hydraulic gradient are sufficient to drive a large water flux. We have changed the corresponding paragraph to be clearer:

  Consequently, $\Phi = \rho_w g b - N + \rho_i g H$ = constant. At the grounding line, boundary conditions (12) require $\Phi(x_g) = 0$. This requires the effective pressure to adjust such that $N = \rho_i g H + \rho_w g b$, that is, the subglacial water content is set by the ice and bed geometry alone, and is independent of the basal melt rate (which is positive throughout, see figure 2_1). This limit is also referred to as height-above-buoyancy or height-above-floatation model (Van der Veen, 1987; Asay-Davis et al., 2016; Kazmierczak et al., 2022) and it~~. This~~ leads to high effective pressure and low water content throughout most of the domain (figure $3b_1$) apart from a small region near the grounding line. Stable steady-state solutions exist, characterised by high ice thickness and surface slopes (figure $3a_1$). In steady state, the water flux is given by (4), i.e., $q_w = \int_0^x m_b \, dx$.

- L 185: you mention fig 5 before fig 4 in the text

  We now reference figure 4 first in the caption of figure 2, which should justify the current ordering of figures.

- L 199: please refer to the corresponding figure to find directly the order of magnitude of variations and the time scale

  Done.

- L209: Figure 5e

  Changed.

- L222: subglacial water fluxes

  Changed.

- L232-238: basal melt rate

  Changed.

- L238-235: Please add numerical values to your analysis.

  The conductive cooling term and basal melt rate are spatially and temporally variable, so that a single number cannot be assigned to these. Moreover, the aim of our study is to investigate general processes, rather than a specific glacier. Focussing on specific numbers could be misleading, as qualitatively similar results could be easily obtained with different parameter choices. That said, we now specify that the oscillation period is ≈ 800 yrs.

- L250-256: Also, remind us which figure we should observe.

  Added references to the relevant figures and panels throughout.

- L250: "significant" – Maybe provide a numerical value, if one is available?

  rephrased to:

  At high effective stress basal melt rates in this boundary layer ~~dissipates significant heat~~ are high ($\approx$ 10 mm yr^{-1}), quickly lowering ~~its own~~ the effective pressure, which then speeds up the flow immediately upstream.

2.4 Discussion

- L261: I would nuance this statement by adding "namely"

  Unsure which statement this refers to? The sentence in question is

  Subglacial conditions affect marine ice sheet dynamics through the basal shear stress, which depends on the effective pressure.

  We've opted to leave it unchanged.

- L263: specify the kind of subglacial drainage system

  Changed to: *We find that the efficiency of a distributed subglacial drainage system alters ~~controls~~ the mode of grounding line dynamics.*

- L264: maybe remind the reader that low hydraulic conductivities lead to high subglacial water storage and reduce effective pressure

  Changed to *Lower hydraulic conductivities result in more water storage, lower effective pressure, and consequently lower basal resistance and faster flow, [...]*

- L288: indicate

  Changed.

- L299: Do you obtain such a result also because you considered more things in your "hydraulic conductivity parameter" ?

  We have completely revised this section in response to a comment by reviewer 1. The limitations and implications of the hydraulic model should now be clearer.

- L306: maybe add reference like Schroeder, D. M., Blankenship, D. D., Young, D. A., Witus, A. E., & Anderson, J. B. (2014). Airborne radar sounding evidence for deformable sediments and outcropping bedrock beneath Thwaites Glacier, West Antarctica. Geophysical Research Letters, 41(20), 7200-7208.

  Done.

- L307: and deforming the bed composed of till/sediments

  As above, we have opted to leave the sentence as is, as the current formulation does not exclude the possibility of till deformation, but avoids discussion how much the till around conduits actually deforms (see for example Damsgaard et al., 2017).

- L313: Papers like Hager 2022 and Dow 2022 consider channels in WAIS. Maybe add a sentence assuming that their existence is plausible in WAIS too.
  Hager, A. O., Hoffman, M. J., Price, S. F., & Schroeder, D. M. (2022). Persistent, extensive channelized drainage modeled beneath Thwaites Glacier, West Antarctica. The Cryosphere, 16(9), 3575-3599.
  Dow, C. F. (2022). Hidden rivers under Antarctica impact ice flow and stability. Nature Geoscience, 15, 869-870.

  These references have been added.

2.5 Appendix

L395: Inefficient rather than ineffective (by opposition to "efficient" in line 393).

Changed.

2.6 Figures and table

General comments for the figures : Great figures! However, I always find it clearer when the extreme values of the colorbar are also indicated. Verify that all panels are mentioned and explained in the short text linked to each figure.

Thank you! The colorbars of the figures will be updated and referencing checked.

- Figure 1: not clear that the bed is "downwards"

  We will try to make the downwards slope clearer.

- Table 1: If you don't explain all the parameters in the text, refer to the table. ε, h_m, N_0 are missing from it.

  We have added ε and N_0 (which is also defined in equation (9)). However, there is no variable or parameter h_m, and a file search did not find it – maybe a misread?

- Figure 2: Explain column c and e.

  Done.

- Figure 3: Why showing specifically these values of kappa ? Maybe provide a rationale for that choice.

  All solutions we display were chosen for illustrative purposes. In figure (3), $\kappa = 10^5$ illustrates that the hydraulic potential is constant (red line), $\kappa = 10^2$ is the smallest value of κ for which we still found a steady state, and $\kappa = 5 \times 10^3$ was chosen as a good intermediate example with an hydraulic potential between column a and c. We have added the following sentences to the figure caption:

  Note that the hydraulic potential is constant for $\kappa = 10^5$ (red line in a_1) and gradually increases for decreasing κ (panels a_2 and a_3). $\kappa = 10^2$ is the smallest value of κ for which steady states exist.

- Figure 4: basal melt rate

  Changed.

- Figure 5: Ice discharge / subglacial water

  Changed.

References

X. S. Asay-Davis, S. L. Cornford, G. Durand, B. K. Galton-Fenzi, R. M. Gladstone, G. H. Gudmundsson, T. Hattermann, D. M. Holland, D. Holland, P. R. Holland, D. F. Martin, P. Mathiot, F. Pattyn, and H. Seroussi. Experimental design for three interrelated marine ice sheet and ocean model intercomparison projects: Mismip v. 3 (mismip+), isomip v. 2 (isomip+) and misomip v. 1 (misomip1). *Geoscientific Model Development*, 9(7):2471–2497, 2016. doi: 10.5194/gmd-9-2471-2016. URL `https://www.geosci-model-dev.net/9/2471/2016/`.

I. Bartholomew, P. Nienow, A. Sole, D. Mair, T. Cowton, and M. A. King. Short-term variability in greenland ice sheet motion forced by time-varying meltwater drainage: Implications for the relationship between subglacial drainage system behavior and ice velocity. *Journal of Geophysical Research: Earth Surface*, 117(F3), 2012. doi: 10.1029/2011JF002220.

J. Brondex, O. Gagliardini, F. Gillet-Chaulet, and G. Durand. Sensitivity of grounding line dynamics to the choice of the friction law. *Journal of Glaciology*, 63(241):854–866, 2017. doi: 10.1017/jog.2017.51.

E. Bueler and J. Brown. The shallow shelf approximation as a sliding law in a thermomechanically coupled ice sheet model. *Journal of Geophysical Research*, 114:F03008, doi:10.1029/2008JF001179, 2009.

E. Bueler and W. van Pelt. Mass-conserving subglacial hydrology in the Parallel Ice Sheet Model version 0.6. *Geoscientific Model Development*, 8(6):1613–1635, 2015. doi: 10.5194/gmd-8-1613-2015.

A. Damsgaard, J. Suckale, J. A. Piotrowski, M. Houssais, M. R. Siegfried, and H. A. Fricker. Sediment behavior controls equilibrium width of subglacial channels. *Journal of Glaciology*, 63(242):1034–1048, 2017. doi: 10.1017/jog.2017.71.

C. Dow, N. Ross, H. Jeofry, K. Siu, and M. Siegert. Antarctic basal environment shaped by high-pressure flow through a subglacial river system. *Nature Geoscience*, 15(11):892–898, 2022. doi: 10.1038/s41561-022-01059-1.

S. Ehrenfeucht, E. Rignot, and M. Morlighem. Seawater intrusion in the observed grounding zone of petermann glacier causes extensive retreat. *Geophysical Research Letters*, 51(12):e2023GL107571, 2024. doi: 10.1029/2023GL107571. e2023GL107571 2023GL107571.

G. H. Gudmundsson. Ice-shelf buttressing and the stability of marine ice sheets. *The Cryosphere*, 7: 647–655, 2013. doi: 10.5194/tc-7-647-2013.

G. H. Gudmundsson, J. Krug, G. Durand, L. Favier, and O. Gagliardini. The stability of grounding lines on retrograde slopes. *The Cryosphere*, 6:1497–1505, 2012. doi: 10.5194/tc-6-1497-2012.

A. O. Hager, M. J. Hoffman, S. F. Price, and D. M. Schroeder. Persistent, extensive channelized drainage modeled beneath Thwaites Glacier, West Antarctica. *The Cryosphere*, 16(9):3575–3599, 2022. doi: 10.5194/tc-16-3575-2022.

M. Haseloff and O. V. Sergienko. The effect of buttressing on grounding line dynamics. *Journal of Glaciology*, 64(245):417–431, 2018. doi: 10.1017/jog.2018.30.

M. Haseloff and O. V. Sergienko. Effects of calving and submarine melting on steady states and stability of buttressed marine ice sheets. *Journal of Glaciology*, 68(272):1149–1166, 2022. doi: 10.1017/jog.2022.29.

C. Helanow, N. R. Iverson, L. K. Zoet, and O. Gagliardini. Sliding Relations for Glacier Slip With Cavities Over Three-Dimensional Beds. *Geophysical Research Letters*, 47(3):e2019GL084924, 2020. doi: 10.1029/2019GL084924.

C. Helanow, N. R. Iverson, J. B. Woodard, and L. K. Zoet. A slip law for hard-bedded glaciers derived from observed bed topography. *Science Advances*, 7(20):eabe7798, 2021. doi: 10.1126/sciadv.abe7798. URL `https://www.science.org/doi/abs/10.1126/sciadv.abe7798`.

I. J. Hewitt. Modelling distributed and channelized subglacial drainage: the spacing of channels. *Journal of Glaciology*, 57(202):302–314, 2011. doi: 10.3189/002214311796405951.

R. C. A. Hindmarsh. An observationally validated theory of viscous flow dynamics at the ice-shelf calving front. *Journal of Glaciology*, 58(208):375–387, 2012. doi: 10.3189/2012JoG11J206.

A. Jenkins. Convection-driven melting near the grounding lines of ice shelves and tidewater glaciers. *Journal of Physical Oceanography*, 41(12):2279–2294, 2011.

E. Kazmierczak, S. Sun, V. Coulon, and F. Pattyn. Subglacial hydrology modulates basal sliding response of the Antarctic ice sheet to climate forcing. *The Cryosphere*, 16(10):4537–4552, 2022. doi: 10.5194/tc-16-4537-2022. URL https://tc.copernicus.org/articles/16/4537/2022/.

T. M. Kyrke-Smith, R. F. Katz, and A. C. Fowler. Subglacial hydrology and the formation of ice streams. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science*, 470 (2161):20130494, 2014. doi: 10.1098/rspa.2013.0494.

F. Pattyn, C. Schoof, L. Perichon, R. C. A. Hindmarsh, E. Bueler, B. de Fleurian, G. Durand, O. Gagliardini, R. Gladstone, D. Goldberg, G. H. Gudmundsson, P. Huybrechts, V. Lee, F. M. Nick, A. J. Payne, D. Pollard, O. Rybak, F. Saito, and A. Vieli. Results of the Marine Ice Sheet Model Intercomparison Project, MISMIP. *The Cryosphere*, 6(3):573–588, 2012. doi: 10.5194/tc-6-573-2012. URL http://www.the-cryosphere.net/6/573/2012/.

F. Pattyn, L. Perichon, G. Durand, L. Favier, O. Gagliardini, R. C. A. Hindmarsh, T. Zwinger, T. Albrecht, S. Cornford, D. Docquier, et al. Grounding-line migration in plan-view marine ice-sheet models: results of the ice2sea MISMIP3d intercomparison. *Journal of Glaciology*, 59(215): 410–422, 2013.

A. Robel, C. Schoof, and E. Tziperman. Rapid grounding line migration induced by internal ice stream variability. *Journal of Geophysical Research*, 119(11):2430–2447, doi:10.1002/2014JF003251, 2014.

A. A. Robel, E. DeGiuli, C. Schoof, and E. Tziperman. Dynamics of ice stream temporal variability: Modes, scales, and hysteresis. *Journal of Geophysical Research*, 118(2):925–936, 2013. doi: 10.1002/jgrf.20072.

A. A. Robel, E. Wilson, and H. Seroussi. Layered seawater intrusion and melt under grounded ice. *The Cryosphere*, 16:451–469, 2022. doi: 10.5194/tc-16-451-2022.

H. Röthlisberger. Water pressure in subglacial channels. *Journal of Glaciology*, 11(62):177–203, 1972. doi: 10.3189/S0022143000022188.

C. Schoof. A variational approach to ice stream flow. *Journal of Fluid Mechanics*, 556:227–251, 2006. doi: 10.1017/S0022112006009591.

C. Schoof. Marine ice-sheet dynamics. Part 1. The case of rapid sliding. *Journal of Fluid Mechanics*, 573:27–55, 2007a. doi: 10.1017/S0022112006003570.

C. Schoof. Ice sheet grounding line dynamics: Steady states, stability, and hysteresis. *Journal of Geophysical Research*, 112(F3), 2007b. doi: 10.1029/2006JF000664.

C. Schoof. Ice-sheet acceleration driven by melt supply variability. *Nature*, 468(7325):803–806, 2010. doi: 10.1038/nature09618.

O. Sergienko and D. J. Wingham. Diverse behaviors of marine ice sheets in response to temporal variability of the atmospheric and basal conditions. *Journal of Glaciology*, pages 1–12, 2024.

O. V. Sergienko and D. J. Wingham. Bed topography and marine ice-sheet stability. *Journal of Glaciology*, page 1–15, 2021. doi: 10.1017/jog.2021.79.

A. Sommers, H. Rajaram, and M. Morlighem. Shakti: Subglacial hydrology and kinetic, transient interactions v1.0. *Geoscientific Model Development*, 11(7):2955–2974, 2018. doi: 10.5194/gmd-11-2955-2018.

V. C. Tsai, A. L. Stewart, and A. F. Thompson. Marine ice-sheet profiles and stability under Coulomb basal conditions. *Journal of Glaciology*, 61(226):205–215, 2015.

S. Tulaczyk, W. B. Kamb, and H. F. Engelhardt. Basal mechanics of Ice Stream B, West Antarctica I. Till mechanics. *Journal of Geophysical Research*, 105:463–482, 2000. doi: 10.1029/1999JB900329.

C. J. Van der Veen. The west antarctic ice sheet: the need to understand its dynamics. In C. J. Van der Veen and J. Oerlemans, editors, *Dynamics of the West Antarctic Ice Sheet*, pages 1–16. D. Reidel Publishing Company, 1987. Proceedings of a Workshop held in Utrecht, May 6-8, 1985.

J. S. Walder and A. Fowler. Channelized subglacial drainage over a deformable bed. *Journal of Glaciology*, 40(134):3–15, 1994. doi: 10.3189/S0022143000003750.

J. Weertman. On the sliding of glaciers. *Journal of Glaciology*, 3:33–38, Mar. 1957.

J. Weertman. Stability of the junction of an ice sheet and an ice shelf. *Journal of Glaciology*, 13:3–11, 1974.

L. K. Zoet and N. R. Iverson. A slip law for glaciers on deformable beds. *Science*, 368(6486):76–78, 2020. doi: 10.1126/science.aaz1183.