Response to reviewer 1 (Alexander Robel)

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.

This is a review of the manuscript "Subglacial hydrology regulates oscillations in marine ice streams" by Haseloff et al. for publication in The Cryosphere, prepared by Alexander Robel. This paper describes a 1D model and corresponding results on the coupled variability of marine ice stream flow and subglacial hydrology. It extends prior work by myself and others, considering water flow within subglacial hydrological systems which leads to the emergence of more rapid surge-like ice flow variability in realistic parameter regimes that may help to address certain shortcomings of past models. I think the manuscript is overall well written and the scientific results are robust and thoughtfully laid out. I see no barrier to publication of this in The Cryosphere after some minor revisions.

Conceptual suggestions:

a) I think perhaps one of the more underplayed implications of the results is that the model produces variability at multi-centennial time scales at values of till hydraulic conductivity that may reasonably be expected to occur in reality. Prior models (i.e., Robel et al. 2013, 2014) which do not include subglacial water flow cannot produce ice stream flow oscillations on time scales less than 900 years or so. The best observations we have of ice stream flow variability in the present day (or at least the late holocene) is the Siple Coast, where most evidence points to periodicity in stagnation-activation cycles of 300-500 years. So, this is a very exciting result since it may resolve this issue. It would be worth spending more time on this in the discussion, and also comparing to the results of Mantelli et al. 2016 which is able to produce quasi-periodic variability at similar time-scales by forcing the system with stochastic climate noise.

The following paragraph has been added to the discussion about ice stream variability, section 4.1:

Observations suggest that the Siple Coast ice streams show temporal variability on timescales of 300 to 500 years (e.g., Retzlaff and Bentley, 1993; Hulbe and Fahnestock, 2007; Catania et al., 2012). While previous models have been able to reproduce stagnation and activation cycles, the period of oscillations in these models is generally on the order of 1000 yrs or longer (e.g., MacAyeal, 1989; Robel et al., 2013, 2014). Here, we illustrate that more frequent oscillations might be modulated by subglacial hydrology.

The following has been added to the discussion about model limitations, section 4.4:

More generally, where marine ice streams are in contact with stochastically-varying ocean and atmospheric conditions, their dynamics can significantly diverge from purely deterministic results (e.g., Mantelli et al., 2016; Robel et al., 2018; Christian et al., 2022; Sergienko and Haseloff, 2023).

b) I think you a being too non-committal on the question of what K_d is in reality. On line 298, you say "these values are not straightforwardly transferable to the values of K_d used here. These values do not take the formation of subglacial conduits into account." But you basically have reasonable values for the case where flow occurs entirely through microporous till (K small limit) and where channelization may enhance these values (K intermediate to large). Other studies (Warburton et al., 2020) besides those that you have cited indicate that till under shear in W. Antarctica may have these higher conductivities (without specific evidence for channelization). You should translate these to Kappa in the discussion in 4.3 so readers can understand what these till values mean in the context of your prior results. Ultimately, the strength of these results will rest on whether the reader understands the conditions under which they can be applied to reality, even if uncertainty remains in what exact parameter values are.

Excellent point. We have rewritten the discussion on ice stream hydrology in the following way:

Given the control that effective conductivity of the bed exerts on ice stream dynamics, determining appropriate parameterizations of the effective hydraulic conductivity is crucial. The existence of subglacial till beneath parts of West Antarctica is well established (Blankenship et al., 1986, 1987; Alley et al., 1986; Alley et al., 1987; Peters et al., 2006; Schroeder et al., 2014). Based on these observations, Walder and Fowler (1994) and Ng (2000) propose the existence of subglacial canals partially eroded into the bed and ice. In settings typical for ice streams, the dynamics of these conduits mimic those typical for distributed subglacial systems where the effective pressure decreases with increasing water discharge. ~~*Estimates of hydraulic conductivity of till vary between* 10^{-9} *to* 5×10^{-5} *m s*$^{-1}$ *for different locations (Fountain and Walder, 1998). However, these values are not straightforwardly transferable to the values of* K_d *used here. These values do not take the formation of subglacial conduits into account. Such conduits likely increase the effective hydraulic conductivity and introduce a dependence on the effective pressure. For example, slug tests have yielded enhanced hydraulic conductivities of unconsolidated sediments close to a subglacial channel (from* 10^{-3} *to* 10^{-2} *m s*$^{-1}$*, Kulessa et al., 2005).*~~ *Assuming the same qualitative behaviour as Walder and Fowler (1994), we model subglacial water flow following a Darcian-style description (e.g., Hewitt, 2011; Flowers, 2015) with* $K_{d,eff}$ *the effective hydraulic conductivity. In our model,* $\kappa = 1$ *corresponds to* $K_d = 3 \times 10^{-4}$ *m s*$^{-1}$ *and at* $N = 100$ *kPa we get* $K_{d,eff} = K_d N_c/N = 6 \times 10^{-3}$ *m s*$^{-1}$*. This is consistent with in-situ measurements of the hydraulic conductivity at the base of Whillans Ice stream, where a minimum of* $K = (0.5$ *to* $1.4) \times 10^{-3}$ *m s*$^{-1}$ *has been estimated (Engelhardt and Kamb, 1997).*

However, such high hydraulic conductivities are inconsistent with subglacial water flow within the void space of the till alone. For example, for subglacial tills derived from Whillans ice stream, Leeman et al. (2016) find conductivities around 10^{-12} *m s*$^{-1}$*. Measurements in the field report values around* 2×10^{-9} *m s*$^{-1}$ *(Engelhardt et al., 1990). Moreover, the Kozeny–Carman relationship* $K \propto e^3/(1+e)$ *is typically used for flow of water in the void space* e *of sediment (e.g., Lambe and Whitman, 1991). When combined with the measured dependence of the void ratio on effective pressure (9), a different dependence of* K *on* N *arises than what we assumed here. This might also alter the ice stream dynamics. In our hydraulically-controlled oscillations, the increase of drainage efficiency with lower* N *causes the termination of the fast flow phase, as more water is evacuated as the bed becomes more lubricated. In the Kozeny–Carman relationship, the dependence on* N *is weaker than in our model, which might not permit the dynamics seen here.*

Assuming that intermediate κ *are representative for West Antarctic ice stream dynamics, alternative pathways must facilitate a more efficient water transport. Engelhardt and Kamb (1997) suggest that a distributed system of sediment-incised canals, as proposed by Walder and Fowler (1994) is most compatible with their observations. Between these canals, water might flow in a thin film at the ice bed-interface, rather than in the subglacial sediment, further enhancing the hydraulic conductivity (Creyts and Schoof, 2009).*

~~*More generally, modelling West Antarctic basal environments requires models for water flow on soft (permeable and deformable) beds. Most subglacial drainage models are developed for hard (impermeable and undeformable) beds, but the existence of subglacial till beneath parts of West Antarctica is well established (Blankenship et al., 1986, 1987; Alley et al., 1986; Alley et al., 1987; Peters et al., 2006; Schroeder et al., 2014). Based on these observations, Walder and Fowler (1994) and Ng (2000) propose the existence of subglacial canals partially eroded into the*~~

~~bed and ice. In settings typical for ice streams, the dynamics of these conduits mimic those typical for distributed subglacial systems where the effective pressure decreases with increasing water discharge. Assuming the same qualitative behaviour as Walder and Fowler (1994), we have used $K_{d,\text{eff}} \propto 1/N$. However, a more complicated relationship is not only possible but likely for realistic ice streams, where a range of subglacial drainage systems might exist at the same value of N (Flowers, 2015). In particular,~~

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 increase~~s~~ 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). We ~~would~~ also expect the conductivity to vary locally, so that we interpret $K_{d,\text{eff}}$ as an effective hydraulic conductivity, averaged over spatial scales resolvable in ice sheet models.

c) I see that there is some discussion of the numerics in the appendix, but it would be useful to summarize in the model description sections how the equations are discretized and solved (seemingly some large nonlinear solve in Petsc). Particularly because activation/surge-type behavior in models is notoriously resolution dependent and you do reference the computational intensity of these simulations in your discussion.

The section describing the model has been extended in the following way:

The model is implemented in PETSc (Balay et al., 2023)~~using finite differences on a fixed staggered grid with an implicit time-step~~. PETSc's SNES library for solution of nonlinear systems of algebraic equations is used to solve individual equations. The equation for momentum balance (2) and subglacial drainage (4)–(9) are discretised using conservative finite differences with implicit timesteps (Katz et al., 2007). The equation for mass balance (1) is discretised with a third-order upwind scheme. We also use a linear subgrid interpolation at the grounding line (Pattyn, 2003).

At each timestep, we use a segregated loop to solve our model. That is, the equations for mass balance (H), momentum balance (u), and subglacial water content (h_s and h_w) are solved in three independent steps. To ensure that the combined solution at the current timestep is converged, the steps are iterated using a Picard scheme until convergence is achieved. That is, at each timestep t_i we calculate $u(t_i^1)$, $H(t_i^1, x)$, $h_s(t_i^1, x)$ and $h_w(t_i^1, x)$ in the first iteration and use these to continue to calculate $u(t_i^2, x)$, $H(t_i^2, x)$, etc until further iteration does not alter the solution at the current timestep. The size of the timestep is adjusted to achieve convergence of the individual SNES solvers as well as convergence of the segegrated solution in no more than 10 Picard iterations.

The implemented scheme is of $O(\Delta x)$ accuracy, and comparison of steady-state results and timeseries under grid refinement are shown in figure A1. While the qualitative behaviour is consistent for values of $\Delta x \lesssim 1000$ m, convergence requires resolution at 10s of meters. Solutions shown here were calculated at resolutions of $\Delta x = 100$ m or finer. 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.

Minor suggestions:

- L1: semicolon unnecessary

  Changed.

- L6: is there a good reason to use "surge" and "oscillation" terminology separately here. It gives the false impression that these are strongly different phenomena.

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

- L12: mass discharge occurs in regions

  Changed.

- L44: here and throughout this is referred to as the "undrained bed model", but historically Tulaczyk called this the "undrained plastic bed model". Is there a reason for dropping "plastic"?

  Our model is undrained but not fully plastic (see sliding law in equation (3)). Moreover, some of the studies we cite use an undrained but not plastic model, for example Fowler and Johnson (1996).

- L45: subglacial water discharge

  Changed.

- L51: due to flow, water freezes and the ice Changed.

- Figure 1 - great figure! Thanks! :)

- L64: indicate here that this limit goes to the solution given by Tsai Added the following sentence:

  This is the limiting case considered in Tsai et al. (2015).

- L68: at intermediate hydraulic conductivities Changed.

- L76: This is confusing because it implies that the glacier length is a constant 1000 km, but this is merely the scale, and the grounding line evolves (as you explain below). Perhaps reword this. The sentence is now:

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

- L99: only a few models Changed.

- L100: subglacial water mass Changed.

- L109: could reword this to point out that this isn't actually a canal model, just a model for down-gradient porous water flow through till which could incorporate the bulk effect of canals through increased hydraulic conductivity

  Changed the sentence to be more specific:

  Equation (5) is similar to a model of distributed water flow in a system of ~~for~~ subglacial conduits ("canals") eroded into soft beds (Walder and Fowler, 1994).

- L142: sediment from freezing Changed.

- Figure 2: Its a bit confuding as to whether the two columns in the intermediate Kappa range are for different values of Kappa? Perhaps should indicate they are different ranges within the intermediate range? Columns a to d in figure 2 show the same values of κ as figure 4. We will revise the figure to clarify this. We understand "intermediate" as between $\kappa \gg 1$ and $\kappa \ll 1$, but of course that does not mean $\kappa = 1$.

- L149: Please provide a physical justification for why it makes sense that effective pressure goes to zero at the grounding line Edited the sentence to read:

  Assuming ice overburden pressure equal to water pressure at the grounding line, w~~W~~e set the effective pressure to zero at the grounding line [...]

- L170: please indicate the time scales of the upstream traveling wave Added the speed at which upstream and downstream traveling waves propagate.

  Notably, hydraulically controlled oscillations are characterised by a quasi-simultaneous speed-up of the entire ice stream in less than 2 yrs (figure 2d), while thermally controlled oscillations exhibit an activation wave, which travels upstream at about 4 km/yr during the speed-up phase (figure 2a). In the regime between these two limiting cases ($\kappa \sim 1$), ice stream activation can occur by downstream propagation of an activation wave at about 2 km/yr (figure 2b).

- L172: different regimes Changed

- L184: N is indicate in row (a), not row (b)? Both. Bed is coloured according to N, but it is plotted also in b to emphasize the boundary layer.

- L188: combine this paragraph with the previous one? Done.

- L190: leads to a local build up in the Changed

- L204: "mechanical barrier upstream of the grounding line" you explain what you mean by this later, but it would be more useful to describe exactly what you mean by this here Changed this to

  This is due to the region of elevated effective pressure and basal shear ~~mechanical barrier~~ upstream of the grounding line becoming less pronounced (compare the regions of elevated effective pressure in figure 4a_4 and b_4).

- L209: a few sentences could be added here describing the variation in oscillation period in more detail - it varies from X yrs to y years over this range of kappa... Extended the sentence to

  The period of hydraulically controlled oscillations decreases from $\approx$ 2000 yrs at $\kappa = 50$ to a minimum of ~~approximately~~ $\approx$300 yrs at $\kappa = 1$; with further reduction of κ the oscillation period increases again up to a period of $\approx$ 800 yrs at $\kappa = 10^{-2}$ (figure 5e).

- Figure 4: not sure what the N_c is doing above the colobar for the N column

  N_c indicated the upper limit of the colorbar. This will be changed to the numerical value.

- L226: see comment for L204 about the "buttress" which is a different term than was used before Changed to

  As in the hydraulically controlled oscillations, the region of elevated effective pressure and basal shear stress downstream of the surge front acts as a buttress to the overall flow.

- L249: would be prudent to also cite Fowler & Schiavi 1998 where many of these ideas originated Done.

- Figure 5b/e: I don't think the y-axis needs a log-scale, obscures some of the variation that occurs here We will adjust figures as appropriate.

- L263: yes, but you hold everything else constant, so this line reads as a bit absolute given that you don't (in this study) vary other parameters Changed "controls" to "alters" .

- L270: surging mountain glaciers? Changed.

- L274: basal temperature gradient? Changed gradient to transition.

- L276: by upstream-traveling activation waves Changed to

  Recent observations have also shown that some surges are instead characterised by ~~upwards travelling~~ activation waves travelling upglacier

- L282: in some sense your study shows this as well, since climatic and gemoetric factors also enter into Kappa, which is the relevant parameter of this study Indeed. Added the following sentence

  This is supported by the appearance of the accumulation rate a and the characteristic ice sheet extent L_x in the ratio of water velocity to ice velocity κ (14a).

- L288: do no always apply when basal Changed.

- L289: The study by Robel et al. 2016 in TC shows that thermal oscillations can temporarily mitigate a positive feedback of grounding line flux and thickness on retrograde slopes. May be useful to make the connection to MISI-style arguments here

  Added the following sentence:

  Previous studies investigating grounding line dynamics with evolving boundary conditions have also shown that thermal oscillations can temporarily stabilise grounding lines on retrograde slopes (Robel et al., 2016).

- L291: can change on decadal to centennial time scales (since this is the time scale for passage of activation/deactivation waves, not necessarily the full period of an oscillation) Changed.

- L293: uncertainty in how Changed.

- L294: similar point to #3 above - your model can be used to speak to the computational requirements for simulating these kinds of variability, which currently is a bit glossed over in appendix and not discussed much at all in main text. Would be useful for modelers interested in incorporating these dynamics in large-scale models to have a sense for resolution they should be aiming for. We have extended the description of the numerical solution to provide additional information.

- L333: there is an interesting literature on interactions between ice streams, particularly the water piracy hypothesis (Anadakrishnan and Alley papers 1994 and 1997) that would be worth discussing in the context of your results We have extended the sentence to account for the water piracy hypothesis

  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) and the interaction of neighbouring ice streams. For example, it has been hypothesised that changes in subglacial water pathways might have contributed to the shutdown of Kamb ice stream approximately 140 years ago (e.g., Anandakrishnan and Alley, 1997).

- L347: steady-streaming Left this as is as streaming is the noun here.

- L349: at period from a few centuries to millennia Changed.

- L356: $O(\Delta x)$ accuracy Changed.

Citation: https://doi.org/10.5194/egusphere-2025-204-RC1

References

R. B. Alley, D. D. Blankenship, C. R. Bentley, and S. T. Rooney. Deformation of till beneath ice stream B, West Antarctica. *Nature*, 322:57–59, 1986. doi: 10.1038/322057a0.

R. B. Alley, D. Blankenship, C. Bentley, and S. Rooney. Till beneath ice stream B, 3, Till deformation: Evidence and implications. *Journal of Geophysical Research*, 92:8921–8930, doi:10.1029/JB092iB09p08921, 1987.

S. Anandakrishnan and R. B. Alley. Stagnation of ice stream C, West Antarctica by water piracy. *Geophysical Research Letters*, 24(3):265–268, doi:10.1029/96GL04016, 1997.

S. Balay, S. Abhyankar, M. F. Adams, S. Benson, J. Brown, P. Brune, K. Buschelman, E. M. Constantinescu, L. Dalcin, A. Dener, V. Eijkhout, J. Faibussowitsch, W. D. Gropp, V. Hapla, T. Isaac, P. Jolivet, D. Karpeev, D. Kaushik, M. G. Knepley, F. Kong, S. Kruger, D. A. May, L. C. McInnes, R. T. Mills, L. Mitchell, T. Munson, J. E. Roman, K. Rupp, P. Sanan, J. Sarich, B. F. Smith, S. Zampini, H. Zhang, H. Zhang, and J. Zhang. PETSc Web page. `https://petsc.org/`, 2023. URL `https://petsc.org/`.

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.

D. D. Blankenship, C. R. Bentley, S. T. Rooney, and R. B. Alley. Seismic measurements reveal a saturated porous layer beneath an active Antarctic ice stream. *Nature*, 322:54–57, 1986. doi: 10.1038/322054a0.

D. D. Blankenship, C. R. Bentley, S. T. Rooney, and R. B. Alley. Till beneath ice stream B. I - Properties derived from seismic travel times. II - Structure and continuity. III - Till deformation - Evidence and implications. IV - A coupled ice-till flow model. *Journal of Geophysical Research*, 92: 8903–8940, 1987. doi: 10.1029/JB092iB09p08903.

G. Catania, C. Hulbe, H. Conway, T. A. Scambos, and C. F. Raymond. Variability in the mass flux of the Ross ice streams, West Antarctica, over the last millennium. *Journal of Glaciology*, 58:741–752, 2012. doi: 10.3189/2012JoG11J219.

J. E. Christian, A. A. Robel, and G. Catania. A probabilistic framework for quantifying the role of anthropogenic climate change in marine-terminating glacier retreats. *The Cryosphere*, 16(7):2725–2743, 2022. doi: 10.5194/tc-16-2725-2022. URL `https://tc.copernicus.org/articles/16/2725/2022/`.

T. T. Creyts and C. G. Schoof. Drainage through subglacial water sheets. *Journal of Geophysical Research*, 114:F04008, doi:10.1029/2008JF001215, 2009.

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.

H. Engelhardt and B. Kamb. Basal hydraulic system of a West Antarctic ice stream: constraints from borehole observations. *Journal of Glaciology*, 43:207–230, 1997.

H. Engelhardt, N. Humphrey, B. Kamb, and M. Fahnestock. Physical Conditions at the Base of a Fast Moving Antarctic Ice Stream. *Science*, 248:57–59, 1990. doi: 10.1126/science.248.4951.57.

G. E. Flowers. Modelling water flow under glaciers and ice sheets. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 471(2176), 2015. ISSN 1364-5021. doi: 10.1098/rspa.2014.0907.

A. C. Fowler and C. Johnson. Ice-sheet surging and ice-stream formation. *Annals of Glaciology*, 23: 68–73, 1996.

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.

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.

C. Hulbe and M. Fahnestock. Century-scale discharge stagnation and reactivation of the Ross ice streams, West Antarctica. *Journal of Geophysical Research*, 112:F03S27, 2007. doi: 10.1029/2006JF000603.

R. Katz, M. Knepley, B. Smith, M. Spiegelman, and E. Coon. Numerical simulation of geodynamic processes with the portable extensible toolkit for scientific computation. *Physics of the Earth and Planetary Interiors*, 163(1):52–68, 2007. ISSN 0031-9201. doi: 10.1016/j.pepi.2007.04.016. Computational Challenges in the Earth Sciences.

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.

T. W. Lambe and R. V. Whitman. *Soil mechanics*, volume 10. John Wiley & Sons, 1991. ISBN 978-0-471-51192-2.

J. R. Leeman, R. D. Valdez, R. B. Alley, S. Anandakrishnan, and D. M. Saffer. Mechanical and hydrologic properties of Whillans Ice Stream till: Implications for basal strength and stick-slip failure. *Journal of Geophysical Research: Earth Surface*, 121(7):1295–1309, 2016. doi: 10.1002/2016JF003863.

D. R. MacAyeal. Large-scale ice flow over a viscous basal sediment - Theory and application to ice stream B, Antarctica. *Journal of Geophysical Research*, 94:4071–4087, 1989. doi: 10.1029/JB094iB04p04071.

E. Mantelli, M. B. Bertagni, and L. Ridolfi. Stochastic ice stream dynamics. *Proceedings of the National Academy of Sciences*, 113(32):E4594–E4600, 2016. doi: 10.1073/pnas.160036211.

F. S. L. Ng. Coupled ice–till deformation near subglacial channels and cavities. *Journal of Glaciology*, 46(155):580–598, 2000. doi: 10.3189/172756500781832756.

F. Pattyn. A new three-dimensional higher-order thermomechanical ice sheet model: Basic sensitivity, ice stream development, and ice flow across subglacial lakes. *Journal of Geophysical Research*, 108: 2382, doi:10.1029/2002JB002329, 2003.

L. E. Peters, S. Anandakrishnan, R. B. Alley, J. P. Winberry, D. E. Voigt, A. M. Smith, and D. L. Morse. Subglacial sediments as a control on the onset and location of two Siple Coast ice streams, West Antarctica. *Journal of Geophysical Research*, 111:B01302, doi:10.1029/2005JB003766, Jan. 2006. doi: 10.1029/2005JB003766.

R. Retzlaff and C. R. Bentley. Timing of stagnation of Ice Stream C, West Antarctica, from short-pulse radar studies of buried surface crevasses. *Journal of Glaciology*, 39(133):553–561, 1993. doi: 10.3189/S0022143000016440.

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, C. Schoof, and E. Tziperman. Persistence and variability of ice-stream grounding lines on retrograde bed slopes. *The Cryosphere*, 10(4):1883–1896, 2016. doi: 10.5194/tc-10-1883-2016. URL https://tc.copernicus.org/articles/10/1883/2016/.

A. A. Robel, G. H. Roe, and M. Haseloff. Response of marine-terminating glaciers to forcing: Time scales, sensitivities, instabilities, and stochastic dynamics. *Journal of Geophysical Research: Earth Surface*, 123(9):2205–2227, 2018. doi: 10.1029/2018JF004709.

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

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

D. M. Schroeder, D. D. Blankenship, D. A. Young, A. E. Witus, and J. B. Anderson. Airborne radar sounding evidence for deformable sediments and outcropping bedrock beneath Thwaites Glacier, West Antarctica. *Geophysical Research Letters*, 41(20):7200–7208, 2014. doi: 10.1002/2014GL061645.

O. Sergienko and M. Haseloff. 'Stable' and 'unstable' are not useful descriptions of marine ice sheets in the Earth's climate system. *Journal of Glaciology*, page 1–17, 2023. doi: 10.1017/jog.2023.40.

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.

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.

K. Warburton, D. Hewitt, and J. Neufeld. Tidal grounding-line migration modulated by subglacial hydrology. *Geophysical Research Letters*, 47(17):e2020GL089088, 2020. doi: 10.1029/2020GL089088.