Annals of Glaciology

Letter

Cite this article: Dow CF (2022). The role of subglacial hydrology in Antarctic ice sheet dynamics and stability: a modelling perspective. *Annals of Glaciology* **63**(87-89), 49–54. https://doi.org/10.1017/aog.2023.9

Received: 15 October 2022
Accepted: 29 January 2023
First published online: 23 March 2023

Keywords:
Antarctic glaciology; glacier hydrology; ice-sheet modelling; subglacial processes

Author for correspondence:
Christine F. Dow,
E-mail: christine.dow@uwaterloo.ca

cambridge.org/aog

The role of subglacial hydrology in Antarctic ice sheet dynamics and stability: a modelling perspective

Christine F. Dow

Department of Geography and Environmental Management, University of Waterloo, Waterloo, Canada

Abstract

Subglacial hydrology is an important component of the ice dynamic system in Antarctica but is challenging to investigate due to the large spatial scales of the catchment systems, the ice thickness, and remote location. Here I discuss key discoveries about Antarctic subglacial hydrology from the Glacier Drainage System (GlaDS) model, including the presence of long, often high-pressure, subglacial channels. These channels pump tens of cubic metres per second of freshwater into ice-shelf cavities and directly affect melt rates at the critical grounding zone regions. Future ice dynamics and ice-shelf cavity models should take subglacial hydrology into account if they are to accurately predict future behaviour of the Antarctic Ice Sheet.

1. Antarctic hydrology

The behaviour of the Antarctic Ice Sheet is critical for predicting rates of global sea level rise. In Antarctica, rates of ice flow into the ocean are largely determined by the driving stress of upstream ice (Seroussi and others, 2020), the buttressing effect of floating ice shelves (Fürst and others, 2016), and conditions at the land-ice basal boundary. Subglacial hydrology plays a crucial role in the latter two processes yet, to date, has not widely been included in ice dynamics or ice/ocean models.

There are two primary reasons why subglacial hydrology has had limited attention in Antarctic research. The first is that the basal system lies underneath multiple kilometres of ice in some of the remotest regions on earth and is therefore difficult to measure directly, for example with borehole drilling, or even indirectly using aerial remote sensing methods. The second reason is that Antarctica, unlike Greenland (Nienow and others, 2017) and alpine (Iken and Bindschadler, 1986) glaciers, has limited or no water input from the surface to the base and therefore no seasonal drivers of hydrological change. Most focus in subglacial hydrology has been on the role of efficient system development over summer melt seasons in non-Antarctic systems (Nienow and others, 1998, 2017) with only minimal efforts to examine steadier winter conditions (Sole and others, 2013; Schoof and others, 2014). Therefore, the Antarctic systems that are largely close to steady-state (over sub-annual periods), with water input only from geothermal heating and ice-bed friction, have garnered less interest. Here I will discuss the important role that subglacial hydrology plays in Antarctic ice dynamics and present results from hydrology modelling over the key regions of Pine Island Glacier and Thwaites Glacier.

2. Subglacial hydrology modelling

To overcome the difficulty of measuring subglacial systems either directly or indirectly, we turn to modelling techniques. Over the last decade, the development of models that incorporate both efficient and inefficient drainage networks (often categorised as channelised and distributed drainage systems that can move water through the subglacial system more or less easily, respectively) has been key for advancing understanding of basal systems for both Antarctica and Greenland, along with glaciers around the world (Flowers, 2015; De Fleurian and others, 2018). The Glacier Drainage System (GlaDS) model (Werder and others, 2013) has been the most widely applied hydrology model in the Antarctic (e.g. Dow and others, 2018c, 2020, 2022; Wei and others, 2020; Indrigo and others, 2021) as its finite element construction allows easily variable mesh refinement. This mesh flexibility means that large catchments can be modelled efficiently with refinement around regions of interest such as subglacial lakes, grounding zones, and fast ice-flow areas. The model simulates distributed systems on the elements and channels on the element edges and allows water exchange between the two systems. The model can therefore be initiated with channels of zero dimension along all element edges, removing the need to predetermine where channels should form; they instead grow naturally as a result of water pressure and flow evolution in the distributed system. The GlaDs model also allows melt and freeze within the distributed elements in addition to the channels (Dow and others, 2018a). Previously, this has been avoided in hydrology models due to the possibility of runaway growth of the distributed system (Kamb, 1987; Schoof, 2010; Schoof and others, 2012). However, direct connection between the elements and element edges in

GlaDS means that additional water not hosted naturally by the distributed system will be rapidly removed by the channels.

One challenge of applying a hydrology model in Antarctica is the lack of data on the subglacial environment. The required inputs to the GlaDS model include basal melt rate, the ice thickness, and basal sliding rate (which controls the opening rate of subglacial cavities and therefore the rate at which the water can increase in pressure). Ice thickness is likely the most well constrained of these with BedMachine using ice dynamics inversion modelling to incorporate radar-derived topographic data into a glaciologically-consistent dataset (Morlighem and others, 2020). Basal melt and sliding velocity are also calculated through model inversion using estimates of geothermal heating and current ice surface velocity (Seroussi and others, 2020). Given the uncertainty associated with these inputs, in particular the geothermal flux rate (Burton-Johnson and others, 2020), sensitivity testing is important for application of hydrology models in Antarctica. For GlaDS, this means comparing outputs from runs with different water input rates and basal sliding velocities to examine the impact that these have on the modelled spatially-variable water pressure, water depth, and channel discharge.

Various parameters in GlaDS such as the conductivity of the distributed and channelised systems are also difficult to constrain and are often applied as spatially uniform values. In reality, the conductivity will likely vary on the scale of metres, if not smaller, but there is no existing method to establish appropriate values over a large area. However, many of the input parameters for GlaDS, such as the distributed system conductivity, linked cavity size, and the bump height at the base of the ice, all have similar effects in determining the speed at which the distributed elements can change pressure. For example, increasing the bump height and increasing the distributed system conductivity both cause the system to reach a steady state with lower water pressure. Therefore, rather than performing sensitivity testing over the full range of each parameter separately, our approach to GlaDS sensitivity testing is to present outputs from systems at the a) upper limit for water pressure, beyond which the model stops converging, b) the lower limit for water pressure, below which the outputs become unrealistic with pressures far below overburden, and c) intermediate pressurisation. If, for example, channels always form in the same place, or fast ice-flow regions are always pressurised near to overburden in each of the sensitivity tests we then know that these are areas of high confidence in our outputs.

Data are available to validate the model outputs, allowing further constraining of the system parameters. Specularity content data, a product of ice penetrating radar processing, indicates regions where water has accumulated (Schroeder and others, 2013). We have previously compared this with model outputs at Aurora Subglacial Basin and found a good correspondence between modelled water pressure and specularity content, although less between modelled water depth and specularity content (Dow and others, 2020). The latter suggests that the uplift of ice by high water pressure is important for producing strong specularity content signals.

3. Key results from GlaDS

To date, Antarctic applications of the GlaDS model include Recovery Glacier (Dow and others, 2018c); Aurora Subglacial Basin draining into Totten and Vanderford glaciers (Dow and others, 2020); David Glacier feeding into Drygalski Ice Tongue (Indrigo and others, 2021); the Weddell Sea region including Institute Ice Stream, Möller Ice Stream, Foundation Ice Stream, Academy Glacier, and Support Force Ice Stream (Dow and others, 2022); and Getz Ice Shelf drainage catchment (Wei and others, 2020). Other modelled regions under development include Wilkes Subglacial Basin, the West Ice Shelf catchment, Denman Glacier, Slessor Glacier, Byrd Glacier, Amery Ice Shelf drainage catchment, and the Siple Coast ice streams (Wearing and others, 2021; Siu and others, 2022). The modelled catchments total to 7,754,220 km^2 and represent ∼60% of the Antarctic basal system. With these modelling applications, some key themes have emerged to illuminate common features of Antarctic basal systems.

3.1. Pine Island and Thwaites glaciers

Here I present model outputs from two regions critical for future Antarctic stability, Pine Island Glacier and Thwaites Glacier. This region of West Antarctica is highly susceptible to rapid retreat through marine ice sheet instability and is showing signs of initial vulnerability (Favier and others, 2014; Joughin and others, 2014). GlaDS was applied to this region with the domain extent calculated from the subglacial drainage catchment assuming hydraulic potential at overburden and the Antarctic Surface Accumulation and Ice Discharge (ASAID) grounding line (Bindschadler and others, 2011). The surface and basal topography are taken from BedMachine Antarctica version 1 (Morlighem and others, 2020), with the basal sliding velocity and melt rates provided from Ice Sheet and Sea-Level System Model (ISSM) inversions (Seroussi and others, 2020). The outputs presented here are for a distributed system conductivity of 1×10^{-4} $m^{3/2}$ $kg^{-1/2}$, a channel conductivity of 5×10^{-2} $m^{3/2}$ $kg^{-1/2}$, and the remaining parameters as shown in Table 1 of Dow and others (2020). The GlaDS equations are detailed fully in Werder and others (2013).

3.2. Development of long subglacial channels

Subglacial channel locations in Antarctica have previously been predicted by comparing hydropotential water flow routing under grounded ice with the location of ice-shelf basal channels (Le Brocq and others, 2013). Hydropotential routing assumes subglacial water pressure is equal to ice overburden pressure, or to a uniform fraction of the ice pressure, and predicts the likely route of water flow without taking channel growth or drainage rates into account (Shreve, 1972). GlaDS has improved on this by not only accounting for dynamic change to water flow, but also providing additional information such as the length of and discharge from subglacial channels. At Thwaites Glacier, the modelled channels run over 170 km to the grounding line in two branches, and join to discharge 80 m^3 s^{-1} into the ice-shelf cavity (Fig. 1d). These values are similar to those obtained using the MPAS-Albany Land Ice (MALI) subglacial hydrology model (Hager and others, 2022). The GlaDS channels show connections between Thwaites subglacial lakes Thw 170, Thw 142, and Thw 124 (Figs. 1d, and 2d), although with different routing than suggested by hydropotential modelling (Smith and others, 2017; Malczyk and others, 2020). At Pine Island Glacier, the primary channel runs through a trough for 124 km and discharges ∼40 m^3 s^{-1} into the ice-shelf cavity (Figs. 1a and c).

These channels are dendritic in nature, similar to those modelled under the Greenland Ice Sheet (Nienow and others, 2017). The primary difference between Greenland and Antarctic channels is that the former grow and shrink seasonally and are often lower pressure than the surrounding distributed system. This is due to the constantly changing water input rate (over hourly to diurnal timescales) allowing channel growth more rapidly than can be offset by creep closure. In contrast, the Antarctic channels are nearer to steady state, with changes over longer time periods (monthly to annual timescales), for example as a result of lake drainage (Livingstone and others, 2022), or alteration in basal velocity (Joughin and others, 2002). Therefore, the Antarctic

https://doi.org/10.1017/aog.2023.9 Published online by Cambridge University Press

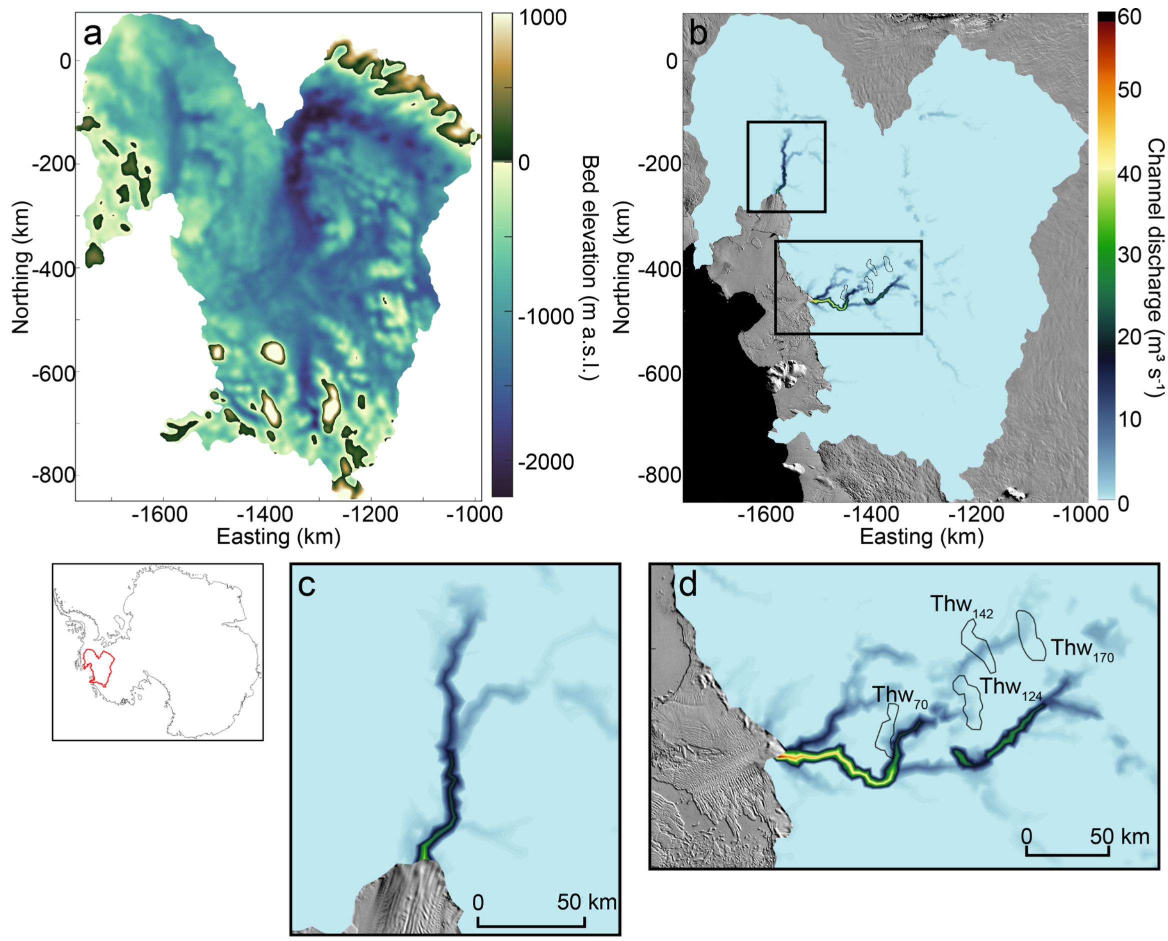

Fig. 1. (a) Basal topography of the Pine Island and Thwaites glaciers, with their location in Antarctica shown in the subset. (b) GlaDS model outputs of channel discharge plotted over the MODIS mosaic of Antarctic (Haran and others, 2014). Black boxes outline the locations of panels c and d. (c) Pine Island Glacier channel discharge. (d) Thwaites Glacier channel discharge, with subglacial lakes outlines from Malczyk and others (2020) shown in black.

channels can reach a near-equilibrium where water pressure in the channel is high (in the realm of 98% of overburden; Dow and others (2022)). This means that, in Greenland, channels are capable of slowing down ice flow by drawing large volumes of water from the surrounding high-pressure distributed system (Nienow and others, 2017). In Antarctica, the difference in water pressure between channels and the distributed system is smaller, reducing the ability of the channel to remove water from the distributed system and slow ice flow (Dow and others, 2022).

3.3. Effects of water pressure on ice flow

Consistently across the Antarctic GlaDs runs, regions of high ice velocity are associated with high-pressure water (Dow and others, 2018c, 2020). This is also the case when basal sliding velocities are applied as a spatially-uniform value in order to remove the circularity of including basal velocity in the GlaDS calculations. At Thwaites and Pine Island glaciers, this relationship of high-pressure water correlated with faster ice velocity breaks down in some regions (Figs. 2a and b). Close to the grounding line, the water pressures are not as high (i.e. close to overburden) as at other systems (e.g. Totten Glacier, Dow and others, 2020). This may be due to a transition from less efficient to more efficient water drainage near the grounding line as discussed by Schroeder and others (2013), who used specularity content data to examine basal hydrological conditions at Thwaites Glacier. Using ISSM to model ice dynamics, McCormack and others (2022a) found that this region transitions from ice motion dominated by basal sliding to a mixed ice deformation and basal sliding regime. It is in this region where our modelled subglacial water pressure at Thwaites Glacier begins to drop (Fig. 2d), and similar low modelled water pressures near the Pine Island grounding line indicate that a transition to mixed deformation and sliding may also exist there (Fig. 2c). This suggests that, unlike in other areas of the Antarctic, such as the Weddell Sea region (Dow and others, 2022), the channels are efficient enough to remove water from the distributed system, allowing the local water pressure to drop.

Current Antarctic ice-flow rates are strongly controlled by ice-shelf buttressing forces. As ice shelves thin or break up, that buttressing force will lessen and the driving stress of interior ice will increase (Seroussi and others, 2020). Higher rates of ice flow will have the dual impact of increasing basal melt from friction and also increasing the surface slope and therefore hydraulic potential gradients. Both of these features will further increase the size and efficiency of channels. Near the grounding zone, water will likely begin to accumulate on the ice surface as the air temperature warms over the next century (Trusel and others, 2015; Nowicki and others, 2020). If this water can hydrofracture through to the ice-bed interface and form moulins, Antarctic ice streams may become more similar to the current seasonally-driven Greenlandic systems where fast ice flow only occurs during part of the year.

3.4. Water flow into ice-shelf cavities

The concentrated flux of freshwater into ice-shelf cavities from channels has been shown to be a key component of ice-shelf melt in the grounding zone (Wei and others, 2020; Dow and

https://doi.org/10.1017/aog.2023.9 Published online by Cambridge University Press

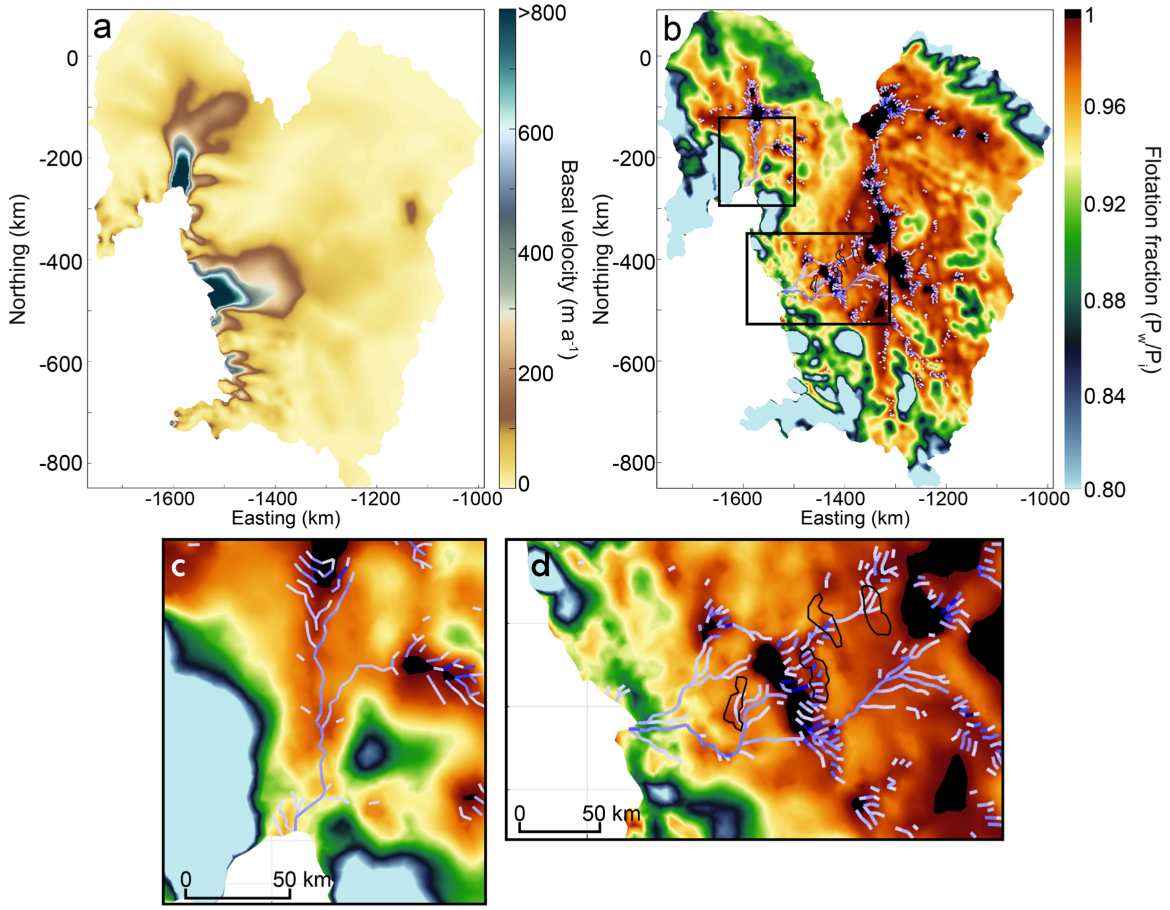

Fig. 2. (a) Basal ice velocity from ISSM inversions. (b) GlaDS model outputs of basal water pressure as a fraction of overburden pressure. The purple lines show the location of subglacial channels. The black boxes outline the locations of panels c and d. (c) Pine Island Glacier water pressure. (d) Thwaites Glacier water pressure, with subglacial lakes outlines from Malczyk and others (2020) shown in black.

others, 2022). The freshwater is more buoyant than the ocean water, rises from the grounding line to the ice-shelf base, and can bring deep, relatively warm water with it (Jenkins, 2011). The most obvious manifestation of this is in the form of basal channels carved into the underside of ice shelves (Le Brocq and others, 2013). These can be hundreds of metres in width and depth and are both visible and measurable on the ice-shelf surface due to hydrostatic balancing (Alley and others, 2016). The role of these channels in ice shelf stability is still a question for future research but it has been shown that some are associated with transverse fractures that can lead to calving events (Dow and others, 2018b).

There is evidence that, in general, the outflow from subglacial channels is associated with higher melt rates at the grounding zone even in the absence of ice-shelf basal channels (Wei and others, 2020; Hager and others, 2022; Dow and others, 2022). The grounding zone is a critical area for ice sheet stability where thinning of floating ice could result in grounding line retreat, a particular concern for grounding zones perched at the top of reverse slopes (Reese and others, 2018). The rates of modelled channelised discharge into the Thwaites and Pine Island ice-shelf cavities (~80 and 40 $m^3 s^{-1}$, respectively) are greater than others modelled using GlaDS and the same ISSM basal melt data product. For example, Totten Glacier and Foundation Ice Stream-Academy Glacier both had modelled channel discharge of ~25 $m^3 s^{-1}$ into the ice-shelf cavity (Dow and others, 2020, 2022). The greater subglacial discharge volumes exiting Thwaites and Pine Island Glacier, in addition to the presence of warm circumpolar deep water in these ice-shelf basins (Paolo and others, 2015), suggests that subglacial hydrology outflow may play a crucial role in the grounding zone melt rates, and therefore stability, in these regions.

4. Future outlook of Antarctic hydrology

4.1. Coupled modelling

Currently, most models of subglacial hydrology are run independently of ice dynamics, without accounting for the effects of changing ice sheet geometry on the subglacial system, or using the modelled water pressure to inform ice sheet sliding rates. Progress has been made in Greenland hydrology where GlaDS has been coupled to Elmer/Ice and applied to Store Glacier (Cook and others, 2020, 2022). GlaDS has also been written into ISSM and applied to Petermann Glacier (Ehrenfeucht and others, 2023). The latter is coupled one-way, in that the effective pressure drives ice dynamics but not the reverse.

The next step for Antarctic subglacial hydrology is to fully couple GlaDS to ice dynamics and run models for both current systems and future scenarios. A coupled modelling approach would be particularly valuable for investigating the impact that seasonal surface-to-bed drainage will have on the basal boundary conditions and ice-flow speed, if moulins begin to form in Antarctica as surface melt increases with warming air temperatures (Trusel and others, 2015). Furthermore, coupling could allow examination of time-transgressive changes to hydrology such as from changes in basal ice velocity (altering the volume of basal melt produced along with cavity opening rates) and ice surface slope.

On the other side of the domain boundary, the impact of subglacial discharge into ocean cavities has only just begun to be explored

(Nakayama and others, 2021, Pelle and others, 2022). Greenland model runs show that plume outputs from tidewater glaciers can affect circulation in the wider fjord (Slater and others, 2018). Analogously, subglacial water discharge could be important for both local and regional melt in Antarctic ice-shelf cavities. In order to project the stability of ice shelves as oceans warm, subglacial discharge outputs must be included in ice-shelf cavity models. Otherwise, calculations of melt, particularly at the critical grounding line may underestimate reality (Dow and others, 2022).

To fully capture the impact of subglacial water flow on the wider system, the ideal approach would involve a fully coupled subglacial hydrology, ice dynamics, and ice/ocean model. Although this sounds complicated, we are not too far from this achieving this approach, as similar applications have occurred in Greenland (Cook and others, 2022) and begin to be examined in Antarctica, for example at Denman Glacier (Pelle and others, 2022).

4.2. Data collection

Subglacial hydrology models are currently tested against limited in situ or remotely sensed data. There is an urgent need to collect more data in key regions to verify hydrology model outputs.

One major limitation of hydrology models is that basal water inputs rely on geothermal heat estimates applied in inversions of ice dynamics (Seroussi and others, 2020). However, there is a wide range of geothermal products and even less ability than subglacial hydrology to test which output is the most accurate (Burton-Johnson and others, 2020; McCormack and others, 2022b). One option to validate the subglacial hydrology model is to measure grounding line water flux where channels are predicted to exit, and compare with the modelled water volumes. These measurements could be made by AUVs accessing the grounding zone region (Dowdeswell and others, 2008), or by drilling through the ice shelf and installing instrumentation into the cavity where subglacial plumes are predicted to be located. An additional method could involve installing a transect of Autonomous phase-sensitive Radio Echo Sounder (ApRES) instrumentation (Nicholls and others, 2015) on ice shelves just downstream of channel outlets (perhaps guided by the location of ice-shelf basal channels) in order to model the volumes of channelised discharge that would be required to explain the observed melt rates.

On land, various instrumentation options are available to test hydrology modelling outputs. Combined active seismic and transient elecromagnetic (TEM) instrumentation could allow assessment of the volume of water and its salinity (Killingbeck and others, 2022). This method can also be used to investigate the flow of water upstream into the subglacial system from the ocean due to tidal forcing (Horgan and others, 2013). Drilling directly to the basal system could provide highly pertinent information about the subglacial hydrological system, as has been achieved at Subglacial Lake Mercer (Priscu and others, 2021), and Whillans Ice Stream (formerly known as Ice Stream B) in West Antarctica (Engelhardt and Kamb, 1997). However, the costs of mounting in situ geophysical and drilling campaigns, and the limited spatial area they can cover suggests that focussed aerial campaigns are also critical for examining subglacial hydrology. For example, the ICECAP project has provided >400 000 km of radar data over Antarctica to date (pers. comm. J. Greenbaum), and the specularity content data derived from those radar lines for Aurora Subglacial Basin proved important for determining the best GlaDS parameters for application in this region (Dow and others, 2020). Campaigns guided by modelled hydrology could focus on locating channels and high-pressure distributed systems to validate model outputs.

Subglacial hydrology plays an important role in Antarctic ice dynamics both for land ice and for the stability of ice shelves. Modelling the impacts from subglacial hydrology on ice sheet flow and ice shelf melting are critical areas for predicting the future of the ice sheet and global sea level rise. The development of coupled models accounting for the effects of subglacial hydrology on ice and ocean dynamics should also be complemented by strategically focussed data collection campaigns.

Acknowledgements. Thanks go to Mauro Werder for use of the Glacier Drainage System (GlaDS) model and Mathieu Morlighem for provision of basal ice velocity and melt rates from the Ice Sheet and Sea-Level System (ISSM) model. Funding was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC; RGPIN-03761-2017) and the Canada Research Chairs Program (950-231237). Supercomputing resources were provided by Compute Canada. Thanks also to Sue Cook for suggestions on this manuscript and to Kevin Siu for initial setup of the modelled domain.

References

Alley KE, Scambos TA, Siegfried MR and Fricker HA (2016) Impacts of warm water on Antarctic ice shelf stability through basal channel formation. *Nature Geoscience* **9**(4), 290–293. doi:10.1038/ngeo2675

Bindschadler R and 10 others (2011) Getting around Antarctica: new high-resolution mappings of the grounded and freely-floating boundaries of the Antarctic Ice Sheet created for the International Polar Year. *The Cryosphere* **5**, 569–588. doi:10.5194/tc-5-569-2011

Burton-Johnson A, Dziadek R and Martin C (2020) Geothermal heat flow in Antarctica: current and future directions. *The Cryosphere* **14**(11), 3843–3873. doi:10.5194/tc-14-3843-2020

Cook SJ, Christoffersen P and Todd J (2022) A fully-coupled 3d model of a large Greenlandic outlet glacier with evolving subglacial hydrology, frontal plume melting and calving. *Journal of Glaciology* **68**(269), 486–502. doi:10.1017/jog.2021.109

Cook SJ, Christoffersen P, Todd J, Slater D and Chauché N (2020) Coupled modelling of subglacial hydrology and calving-front melting at Store Glacier, West Greenland. *The Cryosphere* **14**(3), 905–924. doi:10.5194/tc-14-905-2020

De Fleurian B and 10 others (2018) SHMIP the subglacial hydrology model intercomparison project. *Journal of Glaciology* **64**(248), 897–916. doi:10.1017/jog.2018.78

Dow CF and 8 others (2018b) Basal channels drive active surface hydrology and transverse ice shelf fracture. *Science Advances* **4**(6), eaao7212. doi:10.1126/sciadv.aao7212

Dow CF and 6 others (2018c) Dynamics of active subglacial lakes in Recovery Ice Stream. *Journal of Geophysical Research: Earth Surface* **123**(4), 837–850. doi:10.1002/jgrf.v123.4

Dow CF and 5 others (2020) Totten Glacier subglacial hydrology determined from geophysics and modeling. *Earth and Planetary Science Letters* **531**, 115961. doi:10.1016/j.epsl.2019.115961

Dow CF, Karlsson NB and Werder MA (2018a) Limited impact of subglacial supercooling freeze-on for Greenland Ice Sheet stratigraphy. *Geophysical Research Letters* **45**(3), 1481–1489. doi:10.1002/grl.v45.3

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

Dowdeswell J and 10 others (2008) Autonomous underwater vehicles (AUVs) and investigations of the ice–ocean interface in Antarctic and Arctic waters. *Journal of Glaciology* **54**(187), 661–672. doi:10.3189/002214308786570773

Ehrenfeucht S, Morlighem M, Rignot E, Dow CF and Mouginot J (2023) Seasonal acceleration of Petermann Glacier, Greenland, from changes in subglacial hydrology. *Geophysical Research Letters* **50**, e2022GL098009. doi:10.1029/2022GL098009

Engelhardt H and Kamb B (1997) Basal hydraulic system of a West Antarctic ice stream: constraints from borehole observations. *Journal of Glaciology* **43** (144), 207–230. doi:10.1017/S0022143000003166

Favier L and 8 others (2014) Retreat of Pine Island Glacier controlled by marine ice-sheet instability. *Nature Climate Change* **4**(2), 117–121. doi:10.1038/nclimate2094

Flowers GE (2015) Modelling water flow under glaciers and ice sheets. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* **471**(2176), 20140907. doi:10.1098/rspa.2014.0907

Fürst JJ and 6 others (2016) The safety band of Antarctic ice shelves. *Nature Climate Change* **6**(5), 479–482. doi:10.1038/nclimate2912
Hager AO, Hoffman MJ, Price SF and Schroeder DM (2022) Persistent, extensive channelized drainage modeled beneath Thwaites Glacier, West Antarctica. *The Cryosphere* **16**(9), 3575–3599. doi:10.5194/tc-16-3575-2022
Haran T, Bohlander J, Scambos T, Painter T and Fahnestock M (2014) Modis mosaic of Antarctica 2008–2009 (moa2009) image map. *Boulder, Colorado USA, National Snow and Ice Data Center* **10**, N5KP8037.
Horgan HJ and 7 others (2013) Estuaries beneath ice sheets. *Geology* **41**(11), 1159–1162. doi:10.1130/G34654.1
Iken A and Bindschadler RA (1986) Combined measurements of subglacial water pressure and surface velocity of Findelengletscher, Switzerland: conclusions about drainage system and sliding mechanism. *Journal of Glaciology* **32**(110), 101–119. doi:10.1017/S0022143000006936
Indrigo C, Dow CF, Greenbaum JS and Morlighem M (2021) Drygalski Ice Tongue stability influenced by rift formation and ice morphology. *Journal of Glaciology* **67**(262), 243–252. doi:10.1017/jog.2020.99
Jenkins A (2011) Convection-driven melting near the grounding lines of ice shelves and tidewater glaciers. *Journal of Physical Oceanography* **41**(12), 2279–2294. doi:10.1175/JPO-D-11-03.1
Joughin I, Smith BE and Medley B (2014) Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica. *Science* **344**(6185), 735–738. doi:10.1126/science.1249055
Joughin I, Tulaczyk S, Bindschadler R and Price SF (2002) Changes in West Antarctic ice stream velocities: observation and analysis. *Journal of Geophysical Research: Solid Earth* **107**(B11), EPM 3-1-3-22. doi:10.1029/2001JB001029
Kamb B (1987) Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. *Journal of Geophysical Research: Solid Earth* **92**(B9), 9083–9100. doi:10.1029/JB092iB09p09083
Killingbeck SF, Dow CF and Unsworth MJ (2022) A quantitative method for deriving salinity of subglacial water using ground-based transient electromagnetics. *Journal of Glaciology* **68**(268), 319–336. doi:10.1017/jog.2021.94
Le Brocq AM and 10 others (2013) Evidence from ice shelves for channelized meltwater flow beneath the Antarctic Ice Sheet. *Nature Geoscience* **6**(11), 945–948. doi:10.1038/ngeo1977
Livingstone SJ and 10 others (2022) Subglacial lakes and their changing role in a warming climate. *Nature Reviews Earth & Environment* **3**(2), 106–124. doi:10.1038/s43017-021-00246-9
Malczyk G, Gourmelen N, Goldberg D, Wuite J and Nagler T (2020) Repeat subglacial lake drainage and filling beneath Thwaites Glacier. *Geophysical Research Letters* **47**(23), e2020GL089658. doi:10.1029/2020GL089658
McCormack F, and 5 others (2022a) Modeling the deformation regime of Thwaites Glacier, West Antarctica, using a simple flow relation for ice anisotropy (ESTAR). *Journal of Geophysical Research: Earth Surface* **127**(3), e2021JF006332.
McCormack FS and 6 others (2022b) Fine-scale geothermal heat flow in Antarctica can increase simulated subglacial melt estimates. *Geophysical Research Letters* **49**(15), e2022GL098539. doi:10.1029/2022GL098539
Morlighem M and 10 others (2020) Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic Ice Sheet. *Nature Geoscience* **13**(2), 132–137. doi:10.1038/s41561-019-0510-8
Nakayama Y, Cai C and Seroussi H (2021) Impact of subglacial freshwater discharge on Pine Island Ice Shelf. *Geophysical Research Letters* **48**(18), e2021GL093923. doi:10.1029/2021GL093923
Nicholls KW and 5 others (2015) A ground-based radar for measuring vertical strain rates and time-varying basal melt rates in ice sheets and shelves. *Journal of Glaciology* **61**(230), 1079–1087. doi:10.3189/2015JoG15J073
Nienow P, Sharp M and Willis I (1998) Seasonal changes in the morphology of the subglacial drainage system, Haut Glacier d'Arolla, Switzerland. *Earth Surface Processes and Landforms* **23**(9), 825–843. doi:10.1002/(ISSN)1096-9837
Nienow P, Sole A, Slater DA and Cowton T (2017) Recent advances in our understanding of the role of meltwater in the Greenland Ice Sheet system. *Current Climate Change Reports* **3**(4), 330–344. doi:10.1007/s40641-017-0083-9
Nowicki S and 10 others (2020) Experimental protocol for sea level projections from ISMIP6 stand-alone ice sheet models. *The Cryosphere* **14**(7), 2331–2368. doi:10.5194/tc-14-2331-2020
Paolo FS, Fricker HA and Padman L (2015) Volume loss from Antarctic ice shelves is accelerating. *Science* **348**(6232), 327–331. doi:10.1126/science.aaa0940
Pelle T, Jenkins A, Dow C and Greenbaum J (2022) A new ice shelf melt model that accounts for freshwater discharge and application to Denman Glacier, East Antarctica. In *EGU General Assembly Conference Abstracts*, pp. EGU22–10439.
Priscu JC and 10 others (2021) Scientific access into Mercer Subglacial Lake: scientific objectives, drilling operations and initial observations. *Annals of Glaciology* **62**(85-86), 340–352. doi:10.1017/aog.2021.10
Reese R, Gudmundsson GH, Levermann A and Winkelmann R (2018) The far reach of ice-shelf thinning in Antarctica. *Nature Climate Change* **8**(1), 53–57. doi:10.1038/s41558-017-0020-x
Schoof C (2010) Ice-sheet acceleration driven by melt supply variability. *Nature* **468**(7325), 803–806. doi:10.1038/nature09618
Schoof C, Hewitt IJ and Werder MA (2012) Flotation and free surface flow in a model for subglacial drainage. part 1. distributed drainage. *Journal of Fluid Mechanics* **702**, 126–156. doi:10.1017/jfm.2012.165
Schoof C, Rada C, Wilson N, Flowers G and Haseloff M (2014) Oscillatory subglacial drainage in the absence of surface melt. *The Cryosphere* **8**(3), 959–976. doi:10.5194/tc-8-959-2014
Schroeder DM, Blankenship DD and Young DA (2013) Evidence for a water system transition beneath Thwaites Glacier, West Antarctica. *Proceedings of the National Academy of Sciences* **110**(30), 12225–12228. doi:10.1073/pnas.1302828110
Seroussi H and 10 others (2020) ISMIP6 Antarctica: a multi-model ensemble of the Antarctic ice sheet evolution over the 21st century. *The Cryosphere* **14**(9), 3033–3070. doi:10.5194/tc-14-3033-2020
Shreve R (1972) Movement of water in glaciers. *Journal of Glaciology* **11**(62), 205–214. doi:10.1017/S002214300002219X
Siu K, Dow C, Morlighem M, McCormack F and Hill T (2022) Modelling subglacial hydrology under future climate scenarios in Wilkes Subglacial Basin, Antarctica. In *EGU General Assembly Conference Abstracts*, pp. EGU22–424
Slater D and 5 others (2018) Localized plumes drive front-wide ocean melting of a Greenlandic tidewater glacier. *Geophysical Research Letters* **45**(22), 12–350. doi:10.1029/2018GL080763
Smith BE, Gourmelen N, Huth A and Joughin I (2017) Connected subglacial lake drainage beneath Thwaites Glacier, West Antarctica. *The Cryosphere* **11**(1), 451–467. doi:10.5194/tc-11-451-2017
Sole A and 6 others (2013) Winter motion mediates dynamic response of the Greenland Ice Sheet to warmer summers. *Geophysical Research Letters* **40**(15), 3940–3944. doi:10.1002/grl.50764
Trusel LD and 6 others (2015) Divergent trajectories of Antarctic surface melt under two twenty-first-century climate scenarios. *Nature Geoscience* **8**(12), 927–932. doi:10.1038/ngeo2563
Wearing M, Dow C, Goldberg D, Gourmelen N and Hogg A (2021) Constraining subglacial melt rates and hydrology in the Amery Ice Shelf catchment using modelling and satellite observations. In *AGU Fall Meeting Abstracts*, Vol. 2021, pp. C23A-08.
Wei W and 10 others (2020) Getz ice shelf melt enhanced by freshwater discharge from beneath the west Antarctic ice sheet. *The Cryosphere* **14**(4), 1399–1408. doi:10.5194/tc-14-1399-2020
Werder MA, Hewitt IJ, Schoof CG and Flowers GE (2013) Modeling channelized and distributed subglacial drainage in two dimensions. *Journal of Geophysical Research: Earth Surface* **118**(4), 2140–2158. doi:10.1002/jgrf.20146