



## Review

**Cite this article:** Pattyn F, Carter SP, Thoma M. 2016 Advances in modelling subglacial lakes and their interaction with the Antarctic ice sheet. *Phil. Trans. R. Soc. A* **374**: 20140296. <http://dx.doi.org/10.1098/rsta.2014.0296>

Accepted: 16 June 2015

One contribution of 17 to a Theo Murphy meeting issue 'Antarctic subglacial lake exploration: first results and future plans'.

### Subject Areas:

glaciology

### Keywords:

subglacial lakes, Antarctica, modelling

### Author for correspondence:

Frank Pattyn

e-mail: [fpattyn@ulb.ac.be](mailto:fpattyn@ulb.ac.be)

# Advances in modelling subglacial lakes and their interaction with the Antarctic ice sheet

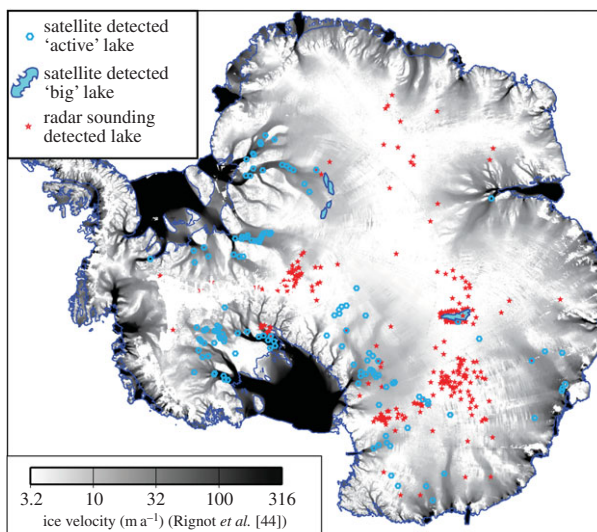
Frank Pattyn<sup>1</sup>, Sasha P. Carter<sup>2</sup> and Malte Thoma<sup>3</sup>

<sup>1</sup>Laboratoire de Glaciologie, Université Libre de Bruxelles (ULB), CP 160/03, Avenue F.D. Roosevelt, 1050 Bruxelles, Belgium

<sup>2</sup>Scripps Institution of Oceanography, University of California, San Diego, CA, USA

<sup>3</sup>Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bussestrasse 24, 27570 Bremerhaven, Germany

Subglacial lakes have long been considered hydraulically isolated water bodies underneath ice sheets. This view changed radically with the advent of repeat-pass satellite altimetry and the discovery of multiple lake discharges and water infill, associated with water transfer over distances of more than 200 km. The presence of subglacial lakes also influences ice dynamics, leading to glacier acceleration. Furthermore, subglacial melting under the Antarctic ice sheet is more widespread than previously thought, and subglacial melt rates may explain the availability for water storage in subglacial lakes and water transport. Modelling of subglacial water discharge in subglacial lakes essentially follows hydraulics of subglacial channels on a hard bed, where ice sheet surface slope is a major control on triggering subglacial lake discharge. Recent evidence also points to the development of channels in deformable sediment in West Antarctica, with significant water exchanges between till and ice. Most active lakes drain over short time scales and respond rapidly to upstream variations. Several Antarctic subglacial lakes exhibit complex interactions with the ice sheet due to water circulation. Subglacial lakes can therefore—from a modelling point of view—be seen as confined small oceans underneath an imbedded ice shelf.



**Figure 1.** The distribution of known subglacial lakes from 2012 against ice velocities [3]. Radar detected lakes are typically found in the interior, whereas active lakes appear in areas of fast flow. ‘Big lakes’ refers to lakes that are sufficiently large that they can be outlined on the map (such as Lake Vostok). The ‘study area’ refers to the Lake Whillans zone that is discussed in detail in §3. The so-called Lakes District is the area of high concentration of subglacial lakes downstream from subglacial Lake Vostok. (Online version in colour.)

## 1. Introduction

Basal conditions of the Antarctic ice sheet, such as basal temperature and hydrological conditions, are largely unknown. However, it is becoming increasingly apparent that subglacial water is omnipresent. Subglacial water potentially lubricates the base, facilitating fast ice flow [1], which demonstrates its importance for ice dynamics. Subglacial water occupies more than 50% of the bed of the Antarctic ice sheet [2] and the majority of that water is stored in subglacial lakes of different sizes. A recent inventory [3] brings the total to almost 400 (figure 1). The majority of subglacial lakes are small (less than 100 km<sup>2</sup>) and are found all across Antarctica. The bigger lakes lie under a thick ice cover of more than 3500 m and are situated close to ice divides. The largest lake is subglacial Lake Vostok, with an area exceeding 10 000 km<sup>2</sup> and containing 5400 ± 1600 km<sup>3</sup> of water [4]. The widespread presence of subglacial lakes inform us on the conditions at the bed, as they point to melting, and therefore allow one to improve thermodynamic ice-sheet models as well as estimates of geothermal heat flow [2,5].

Subglacial lakes actively contribute to basal hydrological dynamics of the Antarctic ice sheet. It was only following the widespread availability of precise repeat pass satellite altimetry, in particular the Ice Cloud and land Elevation Satellite (ICESat) launched in 2003, revealing numerous pockets of subglacial water undergoing repeated episodes of filling and draining that allowed the discovery of ‘active lakes’ [6,7]. These lakes are considerably smaller than the subglacial lakes, such as subglacial Lake Vostok, found in the interior of the (East) Antarctic ice sheet. This discovery of filling and subsequent discharge of Antarctic subglacial lakes [6,8,9] and their association with fast-flow features [7,10] and glacier acceleration [11] has revealed a previously unexpected dynamical behaviour in this subglacial system.

Modelling of ice sheet processes in connection to subglacial lakes is a relatively recent phenomenon. Since the first observation of lake discharge [8], numerical calculations of this discharge led to the identification of the mechanisms of subglacial water transfer over a hard bed [12] through the Nye–Röthlisberger model [13,14] based on mechanisms identified by Evatt

*et al.* [15]. Furthermore, it was demonstrated based on dynamic ice-sheet modelling that rapid discharge of subglacial lakes should be a common phenomenon, as subtle changes in surface topography of the ice sheet may trigger subglacial water transfer [16]. Such connection of subglacial lakes to the hydrological network has mainly been identified for larger subglacial lakes, situated in the interior of the Antarctic ice sheet. Since then, new observations and insights with respect to subglacial lake discharge have led to the development of new models, not only based on hard-bed hydrology, but including water transfer in the presence of porous media, such as subglacial sediment [17,18], and potentially applicable to smaller lakes situated within the more coastal areas of the Antarctic ice sheet as well as beneath ice streams.

However, subglacial lakes not only interact with the overlying ice sheet through water supply and hydrological connections, the water within larger lakes is also affected by lake circulation, thereby influencing the distribution of melting and accretion at the interface between the lake and the overlying ice. Subglacial lakes can therefore be seen as confined small oceans underneath an imbedded ice shelf.

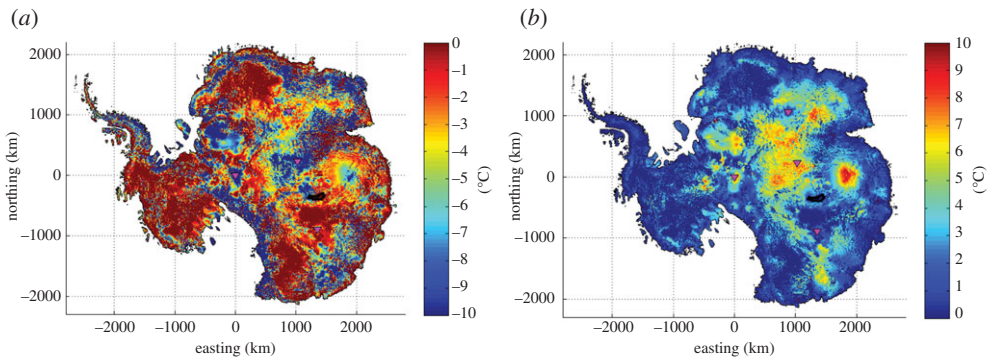
In this overview paper, we report on recent advances in modelling Antarctic subglacial lakes and their interaction with the ice sheet, since the early observations of subglacial lake discharge. For an excellent and comprehensive review of modelling subglacial processes, we refer the reader to the recent paper by Flowers [19]. Here, we focus on recent numerical modelling of subglacial lakes at different spatial scales, ranging from global ice-sheet modelling to high-resolution ice sheet–lake interactions. We therefore assess the basal characteristics of the Antarctic ice sheet, subglacial lake discharges underneath present-day ice streams, and modelling water circulation within large subglacial lakes.

## 2. Modelling Antarctic subglacial conditions using subglacial lake locations

Given the thick insulating ice cover of the Antarctic ice sheet and the low accumulation rates of the interior of the continent, geothermal heat underneath the ice sheet is trapped, despite the cold conditions that are present at the surface. The interplay between geothermal heat flux and accumulation rates is very subtle, as high heat fluxes increase basal temperatures, while high accumulation rates cool down the ice mass through vertical advection of cold ice. To illustrate this, we calculate the minimum geothermal heat flow needed to reach pressure melting point at the bottom of any ice mass as a function of environmental parameters, such as ice thickness and accumulation rate. This can easily be determined analytically [5,20]. Despite the low surface temperatures, pressure melting point is reached for relatively low values of geothermal heat flux, as long as the ice is thick and accumulation rates are small, which is typical for the interior parts of the East Antarctic ice sheet [2,21].

Given that large portions of the Antarctic bedrock are at pressure melting point, numerous subglacial lakes can exist in the centre of the ice sheet. For instance, many subglacial lakes occur in the so-called Lakes District (stretching between subglacial Lake Vostok and Wilkes Land in East Antarctica; figure 1), characterized by a thick ice cover and also low geothermal heat flow [22], combined with low surface slopes and bedrock hollows. Therefore, high geothermal heat fluxes are not a prerequisite for provoking subglacial melt underneath the Antarctic ice sheet.

The uncertainty in geothermal heat seems not so crucial for determining the spatial extent of temperate conditions of the ice sheet in the areas of thickest ice cover and extremely low accumulation rates. However, for most of the ice sheet, geothermal heat flux remains a major unknown for determining the amount of melt, as the ice cover prevents direct measurements. A more advanced way to gauge the basal thermodynamical conditions of the ice sheet is to calculate the heat flow based on the spatial distribution of subglacial lakes underneath the Antarctic ice sheet [2,5]. This is done by calculating the minimum geothermal heat flow needed to keep the base of the ice sheet at pressure melting point at locations of observed subglacial lakes [3], based on a steady-state temperature profile and constrained by observed accumulation rate and ice thickness. Further improvements on estimates of geothermal heat flow consist



**Figure 2.** (a) Mean basal temperature according to the ensemble of 15 experiments, corrected for the dependence on pressure. The lower limit has been cut off at  $-10^{\circ}\text{C}$ . (b) RMSE ( $^{\circ}\text{C}$ ) according to the same ensemble (after [21]). The triangles refer to the location of deep ice core drill sites where englacial temperature profiles are measured and used for the analysis. (Online version in colour.)

of incorporating known basal temperature gradients of observed temperature profiles in deep boreholes [2,5,21]. Such correction on geothermal heat flow is not performed for the size of the lake, but for an influence zone around the lake, based on a Gaussian-shaped influence zone [2,21]. Subsequently, an ensemble run with a full thermomechanically coupled ice sheet model for different geothermal heat flux datasets [22–24] and sizes of influence zones around the lakes then leads to a probabilistic estimate of basal conditions, which are characterized by a mean basal temperature based on 15 ensemble runs, and the associated RMSE based on the same sample (figure 2) [21].

According to figure 2, low values of RMSE correspond to zones where the geothermal heat correction is applied and therefore the difference between the experiments in the ensemble is low. This is also the case for areas where the geothermal heat flow is relatively high, so that for each experiment in the ensemble the pressure melting point is always reached. This is the case for the central part of the West Antarctic ice sheet, as well as extensive zones in the Lakes District. High values of RMSE are found in zones that are unlikely to be at pressure melting point and for which constraints by subglacial lakes are lacking. The overall result is that 55% of the grounded ice sheet is at pressure melting point at the base [2]. Corresponding melt rates give a total melt water volume of  $65\text{ Gt yr}^{-1}$ , or a mean of  $5.3\text{ mm yr}^{-1}$  [2]. The inclusion of a more recent inventory of subglacial lakes [3] as well as up-to-date surface and bedrock topography [25] did not alter these results significantly [21].

### 3. Modelling the connections between subglacial lakes

Subglacial lakes are not only collectors of subglacial meltwater beneath the Antarctic ice sheet, they are also found to actively contribute to the basal hydrological system by episodic discharge of subglacial water [8] and subsequent filling [7]. The development of numerical models of subglacial discharge is relatively recent, following the above-mentioned observations.

Most models for subglacial lakes address at least one of the following processes: lake formation, lake filling, lake drainage and the influence of lakes on the flow of the overlying ice. All of these processes involve the transport of water from high hydraulic potential to low hydraulic potential. Hydraulic potential  $\Theta$  is defined as [26]

$$\Theta = \rho_i g h_i + \rho_w g z_b - N, \quad (3.1)$$

where  $z_b$  is the ice base elevation,  $\rho_i$  and  $\rho_w$  are the ice and water density, respectively,  $h_i$  is the ice thickness and  $N$  is effective pressure (also known as a proxy for basal traction). This

formula makes the flow direction of water about 11 times more sensitive to surface slope than to bed slope.

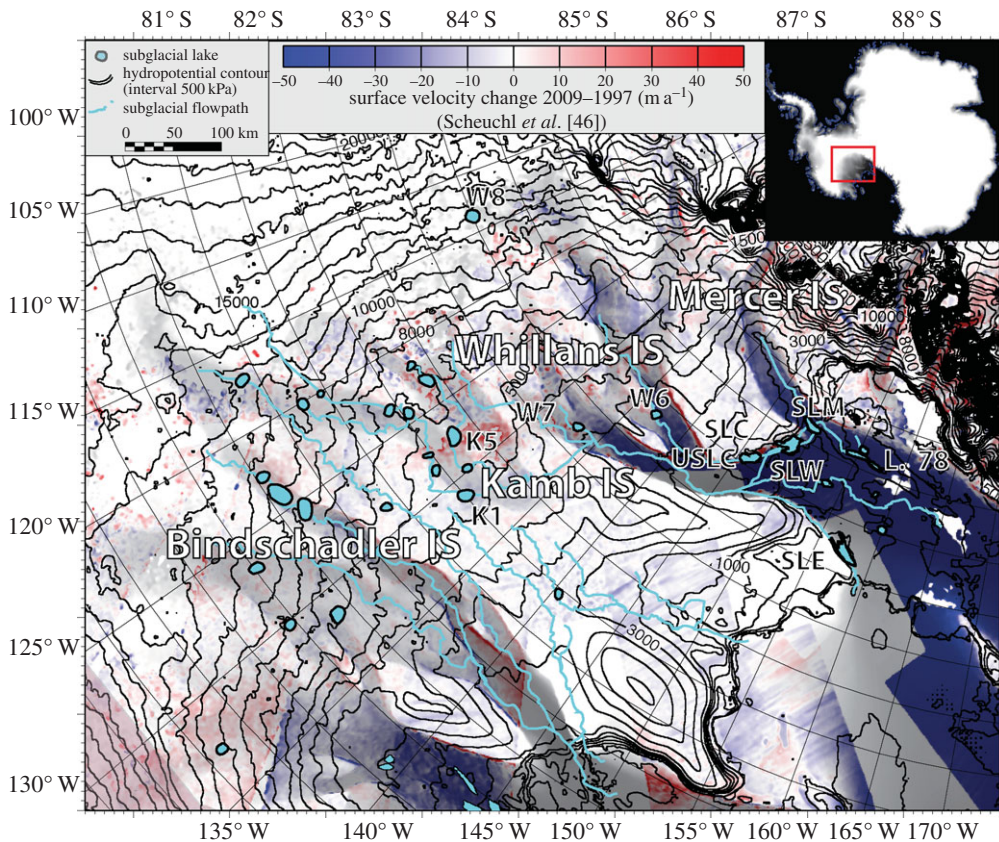
Models addressing lake formation initially just routed water into enclosed local minima in the hydropotential and filled them in until they overflowed at a steady rate [27–29]. Before the identification of active lakes, such depressions were believed primarily to reside in the ice sheet interior near ice divides, where low ice surface relief and high bedrock relief allowed water to be trapped in bedrock hollows [10,30,31]. In fast flowing ice, however, local basal traction highs often termed ‘sticky spots’ [32] can form surface lows in their lee, that also result in hydropotential minima as was observed in the MacAyeal Ice Stream lake system [33] and later modelled [34]. However, not all control is due to ‘sticky spots’; topographical controls for active lakes under ice streams exist as well.

Subglacial discharge models essentially modulate subglacial water discharge through changes in ice sheet surface slope according to equation (3.1). This may lead to periodic outflow of subglacial water and partial discharge triggered by ice flow across a subglacial water cavity [16]. Since the surface elevation not only adapts to changes in subglacial water loss after drainage, but also to visco-plastic ice flow across the lakes, it has been demonstrated that changes in surface elevation do not necessarily reflect the volume of water lost from the subglacial lake cavity [35]. Models addressing the filling of ice-stream lakes have focused primarily on Siple Coast ice streams where ice thickness data are relatively abundant [25] and ice velocity observations have allowed for robust estimates of basal meltwater production rates. With such data, water budget modelling [36,37] demonstrated that the meltwater production rates estimated by Joughin *et al.* [38] can be reproduced when water is allowed to flow down the hydropotential, which resulted in modelled filling rates for the known subglacial lakes downstream that closely matched satellite observations (figure 3). This work also provided evidence in support of two hypothesized episodes of water piracy, the first being that between Kamb and Whillans ice streams believed to have occurred approximately 150 years ago [40] and the second within the lower Whillans ice stream, which occurred in 2005, coincident with heterogeneous thickening of the ice there [41]. Water budgeting has also identified multiple features (e.g. Lake 78 in Whillans ice stream), which appear to be full when through-flow is high (usually due to the drainage of a much larger lake upstream) [41], and then quickly subside once inflow ceases. In areas such as Recovery Glacier [42] and Möller Ice Stream [41,43], a homogeneous melt rate of  $0.7 \text{ mm a}^{-1}$  was found to produce decent agreement between modelled and observed filling rates. In other regions, such as the Aurora basin, obtaining a decent match between modelled and observed filling rates was more difficult [3]. Part of the difficulty reproducing observed inflow rates lies in the uncertainty over the amount of basal meltwater produced, a process that can be quite sensitive to variations in geothermal flux, which varies widely depending upon the technique used to infer it [2,22,23,44]. All studies of water budgeting however agree that in order to reproduce the observed filling rates, the known subglacial lakes require water from a substantial portion of their catchments. Therefore, the filling of active lakes appears to confirm that water is transported from regions of net production to areas where either water is collected in subglacial lakes downstream of the catchment or basal thermal conditions favour removal of water by basal freeze-on.

Despite the fact that the filling rates of lakes in the downstream portions of major ice streams confirm the delivery of water from upstream as predicted in [45], many active lakes are located in places where velocity differencing [46] and/or GPS measurements [47–49] indicate long-term slowdown, as can be seen in figure 3. Understanding this apparent paradox, i.e. that the presence of subglacial water does not necessarily mean that glaciers slide faster across their bed, especially given observations of temporary acceleration during lake drainage events [11], requires a model for the process by which they drain.

The classic model for the drainage of ice dammed lakes in temperate environments favours drainage via a tunnel thermally eroded into an R-channel [14]. Such channels erode through turbulent heat dissipation created by water moving downstream and deform shut in response to pressure differences between the ice and the water in the channel. Initial modelling has shown





**Figure 3.** Map of Siple Coast showing hypopotential and subglacial lakes [9]. Velocities (background shading) are from Rignot *et al.* [39]. Velocity change is from Scheuchl *et al.* [46]. SARIN (synthetic aperture radar interferometry) and LRM (low-resolution mode) refer to the different acquisition modes of CryoSat. (Online version in colour.)

that relatively high effective pressures within the channel could act to siphon water over a topographic seal [50] and that thermal erosion and creep closure result in lakes that fill and drain, even if inflow was constant [51]. Although adaptations in scaling to the R-channel model were made such that it reproduced the timing and magnitude of Antarctic floods [15], a closer look at how these channels might behave beneath Antarctica reveals several problems:

- (i) The hydraulic gradients downstream of major active lakes tend to be several orders of magnitude more gentle than their alpine counterparts, limiting the heat available for melting by turbulent heat dissipation.
- (ii) In polar ice, the englacial temperature gradient would remove some heat that would otherwise be used for melting but, as the channel walls must be at the pressure-melting point, melting will occur simultaneously, inhibiting R-channel growth [52].
- (iii) If such channels were to erode, pressures observed within the subglacial water system would be insufficient to close them at a rate that would stop the flood [53].

Soft sediments, however, may be able to deform shut at lower differential pressures [54]. A simplified model for channelization into the sediment may be sufficient to reproduce the observed filling and drainage cycles of many lakes of the Siple Coast [18], though it has yet to be applied and tested on a broader scale. If this kind of channelization dominates the lake drainage,

it is likely that the formation of lakes tends to spatially concentrate the flow of water into a limited area and then discharges through a system that does not provide lubrication for the ice sheet's base.

Ongoing work suggests that a sediment-channel model [18,55] may only apply to a subset of lakes. Those that formed in bedrock environments, for example, would be unable to drain via channels incised in the sediment. Therefore, a coupled distributed and channelized system that takes into account both porous flow through sediment and/or cavities is needed to properly address this problem in the future. Additionally, the definition of what is a subglacial lake has been expanding in recent years to include ponds and swamps [56,57], and 'ribbed terrane' [58] and even change in storage of subglacial aquifers [17]. Although these means of water storage comprise important parts of the subglacial environment, their evolution and stability on longer time scales is unclear. Most ice-sheet water models still rely on a parametrized film at the ice bed interface (e.g. [29]) and there are clearly diverse approaches how to couple this system. If modelling can be improved, it may provide better clues about the ongoing evolution of our largest ice sheets.

#### 4. Modelling subglacial lake water/ice interaction

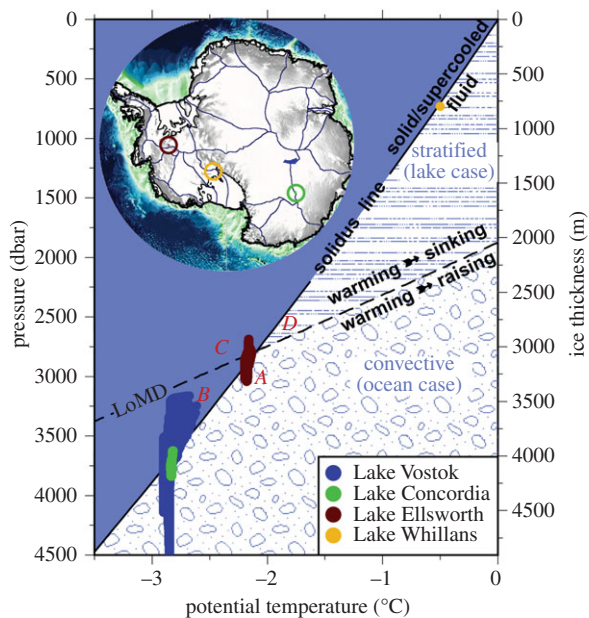
The interaction of ice sheets with subglacial lakes is not only confined to subglacial lake discharge, but is also affected by lake circulation, thereby influencing the distribution of melting and accretion at the interface between the lake and the overlying ice. Subglacial lakes underneath the Antarctic ice sheet may contain water with a very small amount of salinity, as has been observed in subglacial Lake Whillans [59]. They are warmed by the geothermal heat flux at their base and lose energy into the overlying ice sheet at their surface. Because of the pressure-dependent density anomaly of fresh water, two fundamentally different vertical regimes can be found within subglacial lakes, the stratified *lake case* and the convective *ocean case*, which are separated by the pressure-dependent line of maximum density (LOMD) in the parameter space (figure 4). The water temperature of subglacial lakes is close to the *in situ* freezing point, and therefore the lake's depth beneath the Antarctic ice sheet (equivalent to the water pressure) determines which regime dominates the vertical structure within the lake. For instance, the convective case is found in lakes underneath thicker ice.

The horizontal flow is determined by the lake's shape and in particular by the inclined surface where melting (in deeper areas) and freezing (in shallower areas) induce water circulation, even in stratified lakes. Raising of supercooled water (forming platelet ice), with temperatures below the pressure-dependent *freezing point of water*, redistributes ice at the inclined surface, but the ice flow crossing the lake prevents a levelling of the lake-ice interface.

Based on these fundamental physical considerations, early studies tried to assess the water circulation within subglacial Lake Vostok and the mass balance at the ice-lake interface by constraining simplified hydrodynamic equations with rough estimates for the lake geometry [62, 63]. This largest known subglacial lake is located well below the LOMD, hence its thermodynamic regime follows the ocean case. However, these simplified approaches led to contradictory results and argued for a more sophisticated numerical investigation.

For this purpose, a three-dimensional ocean model was adapted to calculate the circulation within subglacial Lake Vostok by solving the full set of primitive equations [64,65]. Although these approaches were numerically much more challenging and provide first insights into the dynamics within the lake, the reliability of these results is limited as they are based on inadequate information about the lake's water column depth. This changed after airborne gravimetric measurements provided sufficient information to infer reliable lake-water depths for subglacial Lake Vostok [4], which were later improved by adding information obtained from seismic profiles [66]. Reliable three-dimensional lake geometries also became available for subglacial Lake Concordia (by airborne gravity measurements) [66], subglacial Lake Ellsworth (by seismic profiling) [67] and subglacial Lake Whillans (by seismic profiling) [68].

The previously used ocean/lake model has been enhanced by, for example, an updated *equation of state*, which calculates the temperature- and pressure-dependent density of water [60],



**Figure 4.** Inset: location of subglacial lakes mentioned in the text. Ice divides and grounding lines are also indicated by black lines. Note that only Lake Vostok is shown in its real size, the locations of the smaller lakes being indicated by circles. Main figure: the solidus line (solid) and line of maximum density (LoMD, dashed) intersect at a critical depth (3050 m) and pressure (2790 dbar) [60,61]. The ice thickness refers to a density of  $917 \text{ kg m}^{-3}$ . The four possible temperature regimes are indicated by red letters. Waters within regions *B* and *C* indicate fluids with supercooled conditions (hence why they appear above the solidus line). The regions of the convective *ocean case* and the stratified *lake case* are separated by the LoMD. The parameter spaces of Lake Vostok (blue), Lake Concordia (green) and Lake Ellsworth (brown) are indicated. Lake Whillans has not been modelled, the circle just indicates its probable condition. Most of the lake volumes are quite homogeneous mixed within the fluid range (below the solidus line). Supercooled, inhomogeneous water masses (above the solidus line) spread only in the uppermost layer close to the lake surface. Therefore, the large covered lake areas above the solidus line are not related to the small supercooled volume within the lakes at all. (Online version in colour.)

and a sophisticated three-equation formulation to estimate the mass balance at the ice–lake interface [69]. This model version is known as ROMBAX [61,70] and has been applied for three different lake geometries (Vostok, Concordia and Ellsworth) to obtain a comprehensive picture about the dynamics and surface mass balance within subglacial lakes [71–74].

Coupling the modelled mass-balance distribution with the ice sheet flow across the lake also gives information about the thickness of the accreted ice layer at the bottom of the Antarctic ice sheet [73–75]. This accreted ice has a different rheology modifying the basal flow [76], and its distribution can provide important information when considering drilling sites to gain direct access to subglacial lakes [67,74].

Finally, combining the lake-flow model ROMBAX with a full-Stokes ice-sheet model [16,77] led us to a fully coupled lake–ice model, which allowed study of the evolution of subglacial lake geometries with adapting areas and water column thicknesses [78,79].

Based on the modelling of three subglacial lakes with very different scales, some general features are found. The inclined lake–ice interface of subglacial lakes initiates a water flow of the order of millimetres to centimetres per second along the lake’s surface. Steeper slopes result in higher velocities, as simulated for subglacial Lake Ellsworth, which has considerably higher ice flow velocities, although its volume is much smaller than the water volume of Lake Vostok (table 1).



**Table 1.** Geometries and modelled results for three subglacial lakes. (Mean values are given here; for an estimation of uncertainties, see [61,74].)

		Vostok	Concordia	Ellsworth
volume	(km <sup>3</sup> )	5000	31	1.4
area	(km <sup>2</sup> )	16 500	617	29
maximum water column	(m)	1100	126	156
surface slope	(m km <sup>-1</sup> )	2	2.5	30
maximum flow velocity	(mm s <sup>-1</sup> )	7	0.1	12
freezing area	(km <sup>2</sup> )	5200	112	19
basal ice loss	(10 <sup>-3</sup> km <sup>3</sup> a <sup>-1</sup> )	50	1.8	0.12
mean melt rate	(mm a <sup>-1</sup> )	28	7.4	75
mean freeze rate	(mm a <sup>-1</sup> )	36	1.5	61
accreted ice area	(km <sup>2</sup> )	11 000	125	25
accreted ice volume	(km <sup>3</sup> )	855	2.0	0.35
mean accreted ice thickness	(m)	70	12	14
mean melt rate in meteoric areas	(mm a <sup>-1</sup> )	17	4	60
lake water residence time	(ka)	52	19	6

Where the ice dips most deeply into the lake, ice melts and supercooled water rises along the surface until it refreezes and platelet ice is formed, accumulating at the lake's ceiling. The magnitude of the lake surface mass balance is equally closely related to the lake surface inclination, resulting in simulated melting (freezing) rates of 7–75 mm a<sup>-1</sup> (1–61 mm a<sup>-1</sup>), respectively (table 1). All three modelled subglacial lakes have a positive mass balance, with respect to the lake surface melting and freezing. However, multi-year measurements of surface elevations indicate that Lake Vostok's water volume remained constant over a period of 5 years [80]. This indicates that water might leak out of the lake. Subglacial linkages between lakes have been reported elsewhere [6,8,29], and most subglacial lakes may well be part of a more widespread subglacial hydrological network underneath the Antarctic ice sheet.

Geothermal heat flow underneath subglacial lakes enables convection in lakes beneath more than approximately 3050 m of ice. This process supports a redistribution of nutrients released by melting ice, which is a necessary requirement to support life within subglacial lakes. Although DNA samples are found in the accreted ice of the Lake Vostok core [81–83], speculations about possible contaminations during drilling raised questions about the results for a long time. However, analyses of water samples taken directly within subglacial Lake Whillans show that a diverse microbial community vitalizes the subglacial hydrological system [84]. Lake Whillans is buried only by about 800 m of ice and therefore should have a stratified water column, indicating that a convective regime seems not a prerequisite for life in subglacial lakes.

The above studies show that understanding subglacial lake circulation and its interaction with the ice sheet requires high-resolution numerical ice sheet and ocean models. The two-way coupling of such models, i.e. the ice sheet thermodynamics providing subglacial melt and refreezing rates to the ocean model and the ocean model providing the thermal boundary to the ice sheet model, results in a complex interaction between both systems which make the problem also a numerical challenge. Unlike an ocean interacting with the ice sheet and ice shelf, subglacial lakes are embedded within the ice sheet, making them not only relatively small, but also a (semi-) closed system that is relatively easy to understand and investigate. Furthermore, the size of subglacial lakes is defined by the water volume within the lake. Hence, the position of the grounding line, i.e. the line separating the grounded from the floating ice, is therefore easily

determined and not a function of the stress balance across the grounding line, as is the case with the ice/ocean boundary. In this way, subglacial lake–ice sheet systems are a good numerical test case for investigating the full coupling of both systems [78].

## 5. Conclusion and outlook

Given the recent discovery and geophysical investigation of subglacial lakes, our understanding of the subglacial Antarctic environment, and the dynamics of subglacial lakes in particular, has fundamentally improved over the last decade. While the study of subglacial lakes is a well-established part of glaciology, understanding of the processes that govern basal melting, subglacial water transport over hard beds and through porous sediments and the interaction with the overlying ice sheet remains rather limited and modelling studies have to simplify these complex processes [19]. Future developments will therefore need to focus on combined hard bed/porous water flow modelling in order to make subglacial hydrological models compliant with pan-Antarctic ice sheet modelling. However, advances in geophysical instrumentation (e.g. ground penetrating radar, satellite altimetry) facilitate the understanding of the subglacial environments, but due to the short observational period, it remains difficult today to elucidate the effect of subglacial dynamics, and subglacial lakes in particular, on the evolution of the Antarctic ice sheet.

Developments in numerical modelling ice sheets and their interaction with subglacial lakes go along with discoveries based on remote sensing of subglacial lake discharge [7] and observations of glacier speedup [11] by trying to explain basic mechanisms of subglacial discharge [16]. Therefore, models are at this stage essentially explaining geophysical processes underneath ice sheets rather than predicting the future behaviour of the ice sheet system [18].

Nevertheless, subglacial lake research increases our knowledge of geothermal heat flow and basal conditions of the Antarctic ice sheet [2] as well as improving our understanding of ice–ocean interactions. From an ice-dynamical point of view, subglacial lakes can be seen as an imbedded ice shelf [85,86]. Both the observation of hydrostatic equilibrium of the overlying ice as well as circulation within lakes lying underneath a thick ice cover corroborate the idea that large subglacial lakes are mini-oceans interacting with the ice sheet and imbedded ice shelf. Subglacial lakes are therefore interesting cases for testing numerical issues with respect to ice sheet–ocean model coupling and may find their way in current and future model intercomparison exercises, such as Marine Ice Sheet–Ocean Model Intercomparison Project.

**Data accessibility.** All material presented in this paper has been published before. The data that have been shown can be accessed via the referenced publications.

**Authors' contributions.** F.P. coordinated the work and wrote most of the manuscript with contributions from S.C. (§3) and M.T. (§4). All authors commented on the manuscript. All authors gave final approval for publication.

**Competing interests.** The authors declare that they have no competing interests.

**Funding.** We received no funding for this study.

**Acknowledgements.** The authors wish to thank both referees for very constructive remarks that improved the manuscript considerably.

## References

1. Bell RE. 2008 The role of subglacial water in ice-sheet mass balance. *Nat. Geosci.* **1**, 297–304. (doi:10.1038/ngeo186)
2. Pattyn F. 2010 Antarctic subglacial conditions inferred from a hybrid ice sheet/ice stream model. *Earth Planet. Sci. Lett.* **295**, 451–461. (doi:10.1016/j.epsl.2010.04.025)
3. Wright AP *et al.* 2012 Evidence of a hydrological connection between the ice divide and ice sheet margin in the Aurora Subglacial Basin, East Antarctica. *J. Geophys. Res. Earth Surface* **117**, F01033. (doi:10.1029/2011JF002066)

4. Studinger M, Bell RE, Tikku AA. 2004 Estimating the depth and shape of subglacial Lake Vostok's water cavity from aerogravity data. *Geophys. Res. Lett.* **31**, L12401. (doi:10.1029/2004GL019801)
5. Siegert MJ. 2000 Antarctic subglacial lakes. *Earth Sci. Rev.* **50**, 29–50. (doi:10.1016/S0012-8252(99)00068-9)
6. Gray L, Joughin I, Tulaczyk VB, Slawekand Spikes, Bindschadler R, Jezek K. 2005 Evidence for subglacial water transport in the West Antarctic Ice Sheet through three-dimensional satellite radar interferometry. *Geophys. Res. Lett.* **32**, L03501. (doi:10.1029/2004GL021387)
7. Fricker HA, Scambos T, Bindschadler R, Padman L. 2007 An active subglacial water system in West Antarctica mapped from space. *Science* **315**, 1544–1548. (doi:10.1126/science.1136897)
8. Wingham DJ, Siegert MJ, Shepherd A, Muir AS. 2006 Rapid discharge connects Antarctic subglacial lakes. *Nature* **440**, 1033–1036. (doi:10.1038/nature04660)
9. Smith BE, Fricker HA, Joughin IR, Tulaczyk S. 2009 An inventory of active subglacial lakes in Antarctica detected by ICESat (2003–2008). *J. Glaciol.* **55**, 573–595. (doi:10.3189/002214309789470879)
10. Bell RE, Studinger M, Shuman CA, Fahnestock MA, Joughin I. 2007 Large subglacial lakes in East Antarctica at the onset of fast-flowing ice streams. *Nature* **445**, 904–907. (doi:10.1038/nature05554)
11. Stearns LA, Smith BE, Hamilton GS. 2008 Increased flow speed on a large East Antarctic outlet glacier caused by subglacial floods. *Nat. Geosci.* **1**, 827–831. (doi:10.1038/ngeo356)
12. Peters NJ, Willis IC, Arnold NS. 2009 Numerical analysis of rapid water transfer beneath Antarctica. *J. Glaciol.* **55**, 640–650. (doi:10.3189/002214309789470923)
13. Nye JF. 1976 Water flow in glaciers: jökulhlaups, tunnels and veins. *J. Glaciol.* **17**, 181–207.
14. Röthlisberger H. 1972 Water pressure in intra- and subglacial channels. *J. Glaciol.* **11**, 177–203.
15. Evatt GW, Fowler AC, Clark CD, Hulton NRJ. 2006 Subglacial floods beneath ice sheets. *Phil. Trans. R. Soc. A* **364**, 1769–1794. (doi:10.1098/rsta.2006.1798)
16. Pattyn F. 2008 Investigating the stability of subglacial lakes with a full Stokes ice-sheet model. *J. Glaciol.* **54**, 353–361. (doi:10.3189/002214308784886171)
17. Christoffersen P, Bougamont M, Carter SP, Fricker HA, Tulaczyk S. 2014 Significant groundwater contribution to Antarctic ice streams hydrologic budget. *Geophys. Res. Lett.* **41**, 2003–2010. (doi:10.1002/2014GL059250)
18. Carter SP, Fricker HA, Siegfried MR. 2015 Active lakes in Antarctica survive on a sedimentary substrate I: theory. *Cryosphere Discuss.* **9**, 2053–2099. (doi:10.5194/tcd-9-2053-2015)
19. Flowers GE. 2015 Modelling water flow under glaciers and ice sheets. *Proc. R. Soc. A* **471**, 20140907. (doi:10.1098/rspa.2014.0907)
20. Hindmarsh RCA. 1999 On the numerical computation of temperature in an ice sheet. *J. Glaciol.* **45**, 568–574.
21. Van Liefferinge B, Pattyn F. 2013 Using ice-flow models to evaluate potential sites of million year-old ice in Antarctica. *Clim. Past* **9**, 2335–2345. (doi:10.5194/cp-9-2335-2013)
22. Shapiro NM, Ritzwoller MH. 2004 Inferring surface heat flux distributions guided by a global seismic model: particular application to Antarctica. *Earth Planet. Sci. Lett.* **223**, 213–224. (doi:10.1016/j.epsl.2004.04.011)
23. Maule CF, Purucker ME, Olsen N, Mosegaard K. 2005 Heat flux anomalies in Antarctica revealed by satellite magnetic data. *Science* **309**, 464–467. (doi:10.1126/science.1106888)
24. Purucker M. 2013 Geothermal heat flux data set based on low resolution observations collected by the CHAMP satellite between 2000 and 2010, and produced from the MF-6 model following the technique described in Fox Maule *et al.* (2005). See <http://websrv.cs.umt.edu/isis/index.php>.
25. Fretwell P *et al.* 2013 Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *Cryosphere* **7**, 375–393. (doi:10.5194/tc-7-375-2013)
26. Shreve RL. 1972 Movement of water in glaciers. *J. Glaciol.* **11**, 205–214.
27. Johnson J, Fastook JL. 2002 Northern hemisphere glaciation and its sensitivity to basal melt water. *Quat. Int.* **95–96**, 65–74. (doi:10.1016/S1040-6182(02)00028-9)
28. Livingstone SJ, Clark CD, Woodward J, Kingslake J. 2013 Potential subglacial lake locations and meltwater drainage pathways beneath the Antarctic and Greenland ice sheets. *Cryosphere* **7**, 1721–1740. (doi:10.5194/tc-7-1721-2013)

29. Goeller S, Thoma M, Grosfeld K, Miller H. 2013 A balanced water layer concept for subglacial hydrology in large-scale ice sheet models. *Cryosphere* **7**, 1095–1106. (doi:10.5194/tc-7-1095-2013)
30. Dowdeswell JA, Siegert MJ. 1999 The dimensions and topographic setting of Antarctic subglacial lakes and implications for large-scale water storage beneath continental ice sheets. *Geol. Soc. Am. Bull.* **111**, 254–263. (doi:10.1130/0016-7606(1999)111<0254:TDATSO>2.3.CO;2)
31. Tabacco IE, Cianfarra P, Forieri A, Salvini F, Zirizotti A. 2006 Physiography and tectonic setting of the subglacial lake district between Vostok and Belgica subglacial highlands (Antarctica). *Geophys. J. Int.* **165**, 1029–1040. (doi:10.1111/j.1365-246X.2006.02954.x)
32. Stokes CR, Clark CD, Lian OB, Tulaczyk S. 2007 Ice stream sticky spots: a review of their identification and influence beneath contemporary and palaeo-ice streams. *Earth-Sci. Rev.* **81**, 217–249. (doi:10.1016/j.earscirev.2007.01.002)
33. Fricker HA, Scambos T, Carter SP, Davis C, Haran T, Joughin I. 2010 Synthesising multiple remote sensing techniques for subglacial hydrologic mapping: application to a lake system beneath MacAyeal Ice Stream, West Antarctica. *J. Glaciol.* **56**, 187–199. (doi:10.3189/002214310791968557)
34. Sergienko OV, Hulbe CL. 2011 ‘Sticky spots’ and subglacial lakes under ice streams of the Siple Coast, Antarctica. *Ann. Glaciol.* **52**, 18–22. (doi:10.3189/172756411797252176)
35. Sergienko OV, MacAyeal DR, Bindschadler RA. 2007 Causes of sudden, short-term changes in ice-stream surface elevation. *Geophys. Res. Lett.* **34**, L22503. (doi:10.1029/2007GL031775)
36. Carter SP, Fricker HA, Blankenship DD, Johnson JV, Lipscomb WH, Price SF, Young DA. 2011 Modeling 5 years of subglacial lake activity in the MacAyeal Ice Stream (Antarctica) catchment through assimilation of ICESat laser altimetry. *J. Glaciol.* **57**, 1098–1112. (doi:10.3189/002214311798843421)
37. Carter SP, Fricker HA. 2012 The supply of subglacial meltwater to the grounding line of the Siple Coast, West Antarctica. *Ann. Glaciol.* **53**, 267–280. (doi:10.3189/2012AoG60A119)
38. Joughin I, Tulaczyk S, Macaeyeal RD, Engelhardt H. 2004 Melting and freezing beneath the Ross ice streams, Antarctica. *J. Glaciol.* **50**, 96–108. (doi:10.3189/172756504781830295)
39. Rignot E, Mouginot J, Scheuchl B. 2011 Ice flow of the Antarctic ice sheet. *Science* **333**, 1427–1430. (doi:10.1126/science.1208336)
40. Anandakrishnan S, Alley RB. 1997 Stagnation of ice stream C, West Antarctica by water piracy. *Geophys. Res. Lett.* **24**, 265–268. (doi:10.1029/96GL04016)
41. Carter SP, Fricker HA, Siegfried MR. 2013 Evidence of rapid subglacial water piracy under Whillans Ice Stream, West Antarctica. *J. Glaciol.* **59**, 1147–1162. (doi:10.3189/2013JoG13J085)
42. Fricker HA, Carter SP, Bell RE, Scambos T. 2014 Active lakes of Recovery Ice Stream, East Antarctica: a bedrock-controlled subglacial hydrological system. *J. Glaciol.* **60**, 1015–1030. (doi:10.3189/2014JoG14J063)
43. Siegert MJ, Ross N, Corr H, Smith B, Jordan T, Bingham RG, Ferraccioli F, Rippin DM, Le Brocq A. 2014 Boundary conditions of an active West Antarctic subglacial lake: implications for storage of water beneath the ice sheet. *Cryosphere* **8**, 15–24. (doi:10.5194/tc-8-15-2014)
44. Llubes M, Lanseau C, Rémy F. 2006 Relations between basal condition, subglacial hydrological networks and geothermal flux in Antarctica. *Earth Planet. Sci. Lett.* **241**, 655–662. (doi:10.1016/j.epsl.2005.10.040)
45. Parizek BR, Alley RB, Hulbe CL. 2003 Subglacial thermal balance permits ongoing grounding-line retreat along the Siple Coast of West Antarctica. *Ann. Glaciol.* **36**, 251–256. (doi:10.3189/172756403781816167)
46. Scheuchl B, Mouginot J, Rignot E. 2012 Ice velocity changes in the Ross and Ronne sectors observed using satellite radar data from 1997 and 2009. *Cryosphere* **6**, 1019–1030. (doi:10.5194/tc-6-1019-2012)
47. Joughin I *et al.* 2005 Continued deceleration of Whillans Ice Stream, West Antarctica. *Geophys. Res. Lett.* **32**, L22501. (doi:10.1029/2005GL024319)
48. Beem LH, Tulaczyk SM, King MA, Bougamont M, Fricker HA, Christoffersen P. 2014 Variable deceleration of Whillans Ice Stream, West Antarctica. *J. Geophys. Res. Earth Surface* **119**, 212–224. (doi:10.1002/2013JF002958)
49. Winberry JP, Anandakrishnan S, Alley RB, Wiens DA, Pratt MJ. 2014 Tidal pacing, skipped slips and the slowdown of Whillans Ice Stream, Antarctica. *J. Glaciol.* **60**, 795–807. (doi:10.3189/2014JoG14J038)



50. Kingslake J, Ng F. 2013 Modelling the coupling of flood discharge with glacier flow during jökulhlaups. *Ann. Glaciol.* **54**, 25–31. (doi:10.3189/2013AoG63A331)
51. Fowler AC. 1999 Breaking the seal at Grimsvotn, Iceland. *J. Glaciol.* **45**, 506–516.
52. Hooke RL, Fastook J. 2007 Thermal conditions at the bed of the Laurentide ice sheet in Maine during deglaciation: implications for esker formation. *J. Glaciol.* **53**, 646–658. (doi:10.3189/002214307784409243)
53. Engelhardt H, Kamb B. 1997 Basal hydraulic system of a West Antarctic ice stream: constraints from borehole observations. *J. Glaciol.* **43**, 207–230.
54. Fowler AC. 2009 Dynamics of subglacial floods. *Proc. R. Soc. A* **465**, 1809–1828. (doi:10.1098/rspa.2008.0488)
55. Ng F. 1998 Mathematical modelling of subglacial drainage and erosion. PhD thesis, University of Oxford, Oxford, UK.
56. Engelhardt H, Kamb B. 2013 Kamb Ice Stream flow history and surge potential. *Ann. Glaciol.* **54**, 287–298. (doi:10.3189/2013AoG63A535)
57. Kyrke-Smith TM, Fowler AC. 2014 Subglacial swamps. *Proc. R. Soc. A* **470**, 20140340. (doi:10.1098/rspa.2014.0340)
58. Sergienko OV, Creyts TT, Hindmarsh RCA. 2014 Similarity of organized patterns in driving and basal stresses of Antarctic and Greenland ice sheets beneath extensive areas of basal sliding. *Geophys. Res. Lett.* **41**, 3925–3932. (doi:10.1002/2014GL059976)
59. Tulaczyk S *et al.* 2014 WISSARD at Subglacial Lake Whillans, West Antarctica: scientific operations and initial observations. *Ann. Glaciol.* **55**, 51–58. (doi:10.3189/2014AoG65A009)
60. Jackett DR, McDougall TJ, Feistel R, Wright DG, Griffies SM. 2006 Algorithms for density, potential temperature, conservative temperature, and the freezing temperature of seawater. *J. Atmos. Ocean. Technol.* **23**, 1709–1728. (doi:10.1175/JTECH1946.1)
61. Thoma M, Grosfeld K, Smith AM, Mayer C. 2010 A comment on the equation of state and the freezing point equation with respect to subglacial lake modelling. *Earth Planet. Sci. Lett.* **294**, 80–84. (doi:10.1016/j.epsl.2010.03.005)
62. Wuest A, Carmack E. 2000 A priori estimates of mixing and circulation in the hard-to-reach water body of Lake Vostok. *Ocean Model.* **2**, 29–43. (doi:10.1016/S1463-5003(00)00007-X)
63. Walsh D. 2002 A note on eastern-boundary intensification of flow in Lake Vostok. *Ocean Model.* **4**, 207–218. (doi:10.1016/S1463-5003(01)00018-X)
64. Williams MJM. 2001 Application of a three-dimensional numerical model to Lake Vostok: an Antarctic subglacial lake. *Geophys. Res. Lett.* **28**, 531–534. (doi:10.1029/2000GL012107)
65. Mayer C, Grosfeld K, Siegert M. 2003 Salinity impact on water flow and lake ice in Lake Vostok, Antarctica. *Geophys. Res. Lett.* **30**, 1767. (doi:10.1029/2003GL017380)
66. Filina IY, Blankenship DD, Thoma M, Lukin VV, Masolov VN, Sen MK. 2008 New 3D bathymetry and sediment distribution in Lake Vostok: implication for pre-glacial origin and numerical modeling of the internal processes within the lake. *Earth Planet. Sci. Lett.* **276**, 106–114. (doi:10.1016/j.epsl.2008.09.012)
67. Woodward J *et al.* 2010 Location for direct access to subglacial Lake Ellsworth: an assessment of geophysical data and modeling. *Geophys. Res. Lett.* **37**, L11501. (doi:10.1029/2010GL042884)
68. Horgan HJ, Anandakrishnan S, Jacobel RW, Christianson K, Alley RB, Heeszel DS, Picotti S, Walter JL. 2012 Subglacial Lake Whillans seismic observations of a shallow active reservoir beneath a West Antarctic ice stream. *Earth Planet. Sci. Lett.* **331–332**, 201–209. (doi:10.1016/j.epsl.2012.02.023)
69. Holland DM, Jenkins A. 1999 Modeling thermodynamic ice–ocean interaction at the base of an ice shelf. *J. Phys. Oceanogr.* **29**, 1787–1800. (doi:10.1175/1520-0485(1999)029<1787:MTIOIA>2.0.CO;2)
70. Thoma M, Grosfeld K, Lange MA. 2006 Impact of the Eastern Weddell Ice Shelves on water masses in the eastern Weddell Sea. *J. Geophys. Res.* **111**, C12010. (doi:10.1029/2005JC003212)
71. Thoma M, Grosfeld K, Mayer C. 2007 Modelling mixing and circulation in subglacial Lake Vostok, Antarctica. *Ocean Dyn.* **57**, 531–540. (doi:10.1007/s10236-007-0110-9)
72. Thoma M, Mayer C, Grosfeld K. 2008 Sensitivity of Lake Vostok's flow regime on environmental parameters. *Earth Planet. Sci. Lett.* **269**, 242–247. (doi:10.1016/j.epsl.2008.02.023)
73. Thoma M, Filina I, Grosfeld K, Mayer C. 2009 Modelling flow and accreted ice in subglacial Lake Concordia, Antarctica. *Earth Planet. Sci. Lett.* **286**, 278–284. (doi:10.1016/j.epsl.2009.06.037)

74. Thoma M, Grosfeld K, Mayer C, Smith AM, Woodward J, Ross N. 2011 The ‘tipping’ temperature within Subglacial Lake Ellsworth, West Antarctica and its implications for lake access. *Cryosphere* **5**, 561–567. (doi:10.5194/tc-5-561-2011)
75. Thoma M, Grosfeld K, Mayer C. 2008 Modelling accreted ice in subglacial Lake Vostok, Antarctica. *Geophys. Res. Lett.* **35**, L11504. (doi:10.1029/2008GL033607)
76. Jouzel J *et al.* 1999 More than 200 meters of lake ice above subglacial Lake Vostok, Antarctica. *Science* **286**, 2138–2141. (doi:10.1126/science.286.5447.2138)
77. Thoma M, Grosfeld K, Barbi D, Determann J, Goeller S, Mayer C, Pattyn F. 2014 RIMBAY: a multi-approximation 3D ice-dynamics model for comprehensive applications: model description and examples. *Geosci. Model Dev.* **7**, 1–21. (doi:10.5194/gmd-7-1-2014)
78. Thoma M, Grosfeld K, Mayer C, Pattyn F. 2010 Interaction between ice sheet dynamics and subglacial lake circulation: a coupled modelling approach. *Cryosphere* **4**, 1–12. (doi:10.5194/tc-4-1-2010)
79. Thoma M, Grosfeld K, Mayer C, Pattyn F. 2012 Ice flow sensitivity to boundary processes: a coupled model study in the Vostok Subglacial Lake area. *Ann. Glaciol.* **53**, 173–180. (doi:10.3189/2012AoG60A009)
80. Richter A *et al.* 2014 Height changes over subglacial Lake Vostok, East Antarctica: insights from GNSS observations. *J. Geophys. Res.* **119**, 2460–2480. (doi:10.1002/2014JF003228)
81. Karl DM, Bird DF, Björkman K, Houlihan T, Shackelford R, Tupas L. 1999 Microorganisms in the accreted ice of Lake Vostok, Antarctica. *Science* **286**, 2144–2147. (doi:10.1126/science.286.5447.2144)
82. Priscu JC *et al.* 1999 Geomicrobiology of subglacial ice above Lake Vostok, Antarctica. *Science* **286**, 2141–2144. (doi:10.1126/science.286.5447.2141)
83. Shtarkman YM, Koer ZA, Edgar R, Veerapaneni RS, Dalia T, Morris PF, Rogers SO. 2013 Subglacial Lake Vostok (Antarctica) accretion ice contains a diverse set of sequences from aquatic, marine and sediment-inhabiting bacteria and eukarya. *PLoS ONE* **8**, e67221. (doi:10.1371/journal.pone.0067221)
84. Christner BC *et al.* 2014 A microbial ecosystem beneath the West Antarctic ice sheet. *Nature* **512**, 310–313. (doi:10.1038/nature13667)
85. Erlingsson U. 2006 Lake Vostok behaves like a captured lake and may be near to creating an Antarctic jokulhlaup. *Geografiska Ann. Ser. A Phys. Geogr.* **88**, 1–7. (doi:10.1111/j.0435-3676.2006.00278.x)
86. Pattyn F. 2011 Antarctic subglacial lake discharges. In *Antarctic subglacial aquatic environments* (eds MJ Siegert, MC Kennicutt), pp. 27–44. Washington, DC: American Geophysical Union. (doi:10.1002/9781118670354.ch3)