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Subglacial lakes and their changing role in a warming climate

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Abstract:

Subglacial lakes store ancient climate records, provide habitats for life, and modulate ice flow, basal hydrology, biogeochemical fluxes and geomorphic activity. In this Review, we construct the first global inventory of subglacial lakes (773 total): 675 from Antarctica (59 newly-identified in this study), 64 from Greenland, 2 beneath Devon Ice Cap, 6 beneath Iceland's ice caps, and 26 from valley glaciers. We use this inventory to evaluate subglacial lake environments, dynamics, and their wider impact on ice flow and sediment transport. Lake behaviour is conditioned by their unique subglacial setting and the hydrologic, dynamic and mass balance regime of the overlying ice mass. We predict that in regions where climate warming causes ice-surface steepening there will be fewer and smaller lakes, but increased activity with higher discharge drainages of shorter duration. Coupling to surface melt and rainfall inputs will modulate fill-drain cycles and seasonally enhance oxic processes. Higher discharges cause large, transient ice-flow accelerations, but might result in overall net slowdown due to development of efficient subglacial drainage. Future subglacial lake research requires new drilling technologies, and the integration of geophysics, satellite monitoring and numerical modelling, which will provide new insight into their wider role in a changing Earth system.

Key Points

- First global inventory of 773 subglacial lakes: 675 from Antarctica (59 newly identified here), 64 from Greenland, 6 from Iceland, 2 beneath Devon Ice Cap and 26 from valley glaciers.
- 80% of lakes are stable, implying closed systems, or that inflow and outflow is approximately balanced; the remainder are active lakes with five distinct activity patterns.
- Active subglacial lakes exhibit a quasi-linear relationship between mean discharge and lake volume; lakes in Greenland and Iceland exhibit higher discharge rates for a given lake volume compared with Antarctica.
- Larger active subglacial lakes recharge at a faster rate than smaller lakes, suggesting an underlying control on lake refilling associated with lake size.
- Where climate warming causes ice-surface steepening lakes become less likely, but drainage will be of higher magnitude producing transient ice-flow perturbations that are more likely to cause a net ice-flow reduction.
- Enhanced surface melt and rainfall inputs to the bed will modulate fill-drain cycles, increase the potential for catastrophic drainages and provide a supply of oxygen, sediment, microbes and nutrients.

Introduction

Subglacial lakes under ice sheets and glaciers (Fig. 1) impact multiple components of the Earth system. Lakes provide viable habitats for microbial communities[2,3] that might have followed unique evolutionary trajectories and serve as analogues for putative extra-terrestrial ecosystems[4]. Water transfer through subglacial lakes modulates basal hydrology[5–9] and biogeochemical fluxes[3,10], and can cause ice-flow variations on sub-decadal time scales[11–14]. Lake drainage transports large volumes of water and sediment downstream[15,16]. Lake sediments contain archives of ice sheet history and climate change[1] similar to ice core records. In Antarctica, water crossing the *grounding line* into sub-ice shelf cavities[6] can alter ice-ocean interactions[17–20] and can modify ocean circulation[21]. Sudden outburst floods onto the glacier foreland form outwash plains (sandurs) and present a major hazard to infrastructure[22].

Subglacial lakes occur when subglacial meltwater collects in local minima of *basal hydrologic potential*, due to depressions in bed topography and the glacier surface, ice flow over 'sticky spots'[23], or trapping of basal water behind *cold based ice*[24]. In Antarctica, the first evidence of subglacial lakes[42,43] came from unusually strong, sharp, continuous and smooth basal reflections detected in airborne *radio-echo sounding* (RES) surveys in the late 1960s. However, lake inventories were not significantly expanded until further RES investigations in the 1990s and 2000s[44,45], while seismic surveying revealed thick water columns[32,46,47]. Between 2005 and 2008 a new class of "active" lakes was discovered through satellite measurements of ice-surface elevation from Envisat/ERS-2 radar and ICESat laser altimetry[4,48,49]. Active subglacial lakes can drain along subglacial flow-paths for hundreds of kilometres, and form connected networks[50,51].

Jökulhlaups in Iceland provide the longest record of subglacial lake activity, having been reported since the Middle Ages and investigated by ground expeditions and aerial reconnaissance since the early 20th Century[36]. Icelandic subglacial lakes form by melting of ice via geothermal heat enhanced by volcanism and influxes of surface meltwater. During lake drainage their overlying ice-surface depressions lower rapidly and slowly recover afterwards as the lake refills[22,37–39]. Elsewhere, small outburst floods have been caused by drainage of large or multiple water-filled subglacial cavities from valley glaciers[40,41].

Over the last decade, subglacial lakes have been discovered under other ice masses, for example, in Greenland[52–54] and the Canadian Arctic[55]. In Greenland, the first putative subglacial lake was inferred from a flat ice-surface elevation anomaly[56]. Since then, interrogation of airborne RES data[52–54] and identification of ice-surface elevation changes from satellite altimetry and high-resolution time-stamped Digital Surface Models (DSMs)[15,54,57,58] confirmed their widespread existence under this ice sheet. The two subglacial lakes identified beneath Devon Ice Cap exist at temperatures well below the pressure-melting point and likely consist of hypersaline water[55].

In this Review, we construct the first global inventory of subglacial lakes, enabling lake characteristics and dynamics to be classified. We frame subglacial lake character and function, and their impact on ice flow, subglacial drainage, sediment transport and biogeochemical fluxes as dependent on the hydrologic, dynamic and mass balance regime of the ice mass above. Using space-time substitution, a conceptual model is proposed for how subglacial lakes, and their influence on the broader environment, will change in a warming world.

Background

Detecting and characterising subglacial lakes

Identification and characterisation of subglacial lakes and their dynamics has largely relied on remote geophysical observations[12,43,54,59–61] (Fig. 2a), due to the challenge of directly accessing and cleanly sampling water and sediments beneath thick ice[62]. Whillans Subglacial Lake[1,63–65] and Mercer Subglacial Lake[66], West Antarctica (~600 m and 1100 m ice thickness) and western Skaftá Lake[67] and Grímsvötn[63], Iceland (~400 and 300 m ice thickness) have been cleanly accessed, while Lake Vostok, East Antarctica (~4000 m ice thickness) was drilled, but samples were contaminated[68]. In the French Alps, the geometry and water level of a small subglacial lake under Glacier de Tête Rousse (76 m ice thickness) was successfully accessed and monitored using boreholes and sonar[69].

Recent innovations in RES have improved detection and characterisation of subglacial water. Increased radar system bandwidth and signal sensitivity have improved the detection, resolution and fidelity of radar reflections[70]. Swath radar technology, enabling (pseudo) 3D imaging of bed topography and englacial layers[71,72], can better resolve basal roughness, hydrological routing and basal melt/freeze-on. Using scattering characteristics of returned bed echoes such as the specularity content[73], trailing bed echoes[74], the bed echo coherent index[75,76] and bed-echo variability[77] has advanced quantitative identification of subglacial water and the understanding of subglacial drainage systems[73,78–80]. Finally, there have been improvements in the automatic detection of subglacial lakes[29,54,81] including utilisation of machine learning algorithms[81]. Despite enhancements in radar technology, some dynamic lakes may not have particularly smooth ice-water interfaces, making interpretation of specularity problematic.

While radar sounding can measure lake extent, seismic reflection surveys are necessary to reveal water column thickness and structure of lake sediments[32,47,60,82,83]. Active seismic surveys using innovative survey design and analysis (e.g., acoustic impedance or Amplitude Versus Angle) can confirm the presence of a subglacial lake and characterize lake floor properties (i.e., hard bedrock vs. sediment, till porosity)[47,60]. Other geophysical methods, gravimetry for deeper structure, and electromagnetic (EM) approaches, can reveal the geological and hydrological setting surrounding subglacial lakes[84–86].

Satellite observations of ice-surface displacement derived from Interferometric Synthetic Aperture Radars (InSAR) on ERS-2[5], Radarsat[87] and the Advanced Land Observing Satellite (ALOS)[88], together with elevation measurements from satellite radar and laser altimeters on ERS-2[5], Envisat[51], ICESat[49] and CryoSat-2[6,88–90] have proved crucial in detecting indirect subglacial lake activity, and for estimating their change in volume. In particular, improvements in the accuracy, coverage and record length of the new generation of polar orbiting altimeters, starting with CryoSat-2 in 2010, is enabling a transition from opportunistic studies to operational, near-real-time monitoring of subglacial lake activity[6]. Most recently, Sentinel-3 (2016 onwards) and ICESat-2 (2018 onwards) have been used to monitor subglacial lake activity[91,92] (Fig. 2b). Sentinel-3 provides frequent (27-day) temporal sampling and – as an operational mission – guarantees long-term continuity of measurements. ICESat-2 with its 40 m along-track spacing and sub-decimeter precision[93,94] provides unprecedented spatial and temporal sampling of subglacial lake activity[95] (Fig. 2b).

While monitoring active (10 km)-scale Antarctic lakes by satellite altimeters is well established, the discovery of numerous smaller (<1 km) lakes in Greenland[54] presents an observational challenge. Recent, exploratory work utilised timestamped DSMs (e.g. ArcticDEM, REMA and TanDEM-X), generated from super high resolution (1-10 m) stereoscopic optical imagery[96,97], or single pass radar interferometry. These data can detect detailed patterns of surface deformation associated with lake volume changes, with high vertical precision[15,58]. Small lakes (<2 km) beneath valley glaciers have also been identified using InSAR to measure ice-surface elevation changes[98].

Subglacial lake distribution and hydrology

Subglacial lakes have been predicted[8,105–107] and identified[54,55,98,108] in diverse settings. Previous inventories have focused on lakes beneath individual ice masses. The last inventory of Antarctica in 2012 contained 379 subglacial lakes[108], while 60 subglacial lakes were identified beneath the Greenland Ice Sheet in 2019 based on an ice-sheet-wide survey and the published literature[54]. Despite a long history of research into Iceland subglacial lakes[22,37–39,67,109–111], there is no formal complete inventory.

Subglacial lake locations and volumes are determined by the subglacial hydrology, which results from subglacial water production and the surface and bedrock topography. The distribution and production rate of subglacial water is controlled by the insulation and pressure of the overlying ice sheet[99], geothermal heat (an extreme example is sub-ice volcanism in Iceland[22]), frictional heat generated by fast-flowing ice streams or outlet glaciers[99], and surface water injections[100] (Fig. 1). The flow and storage of subglacial water is governed by basal hydrologic potential[101]: The ice-surface gradient is ~10x as important as the bedrock gradient in controlling hydrologic potential and is therefore likely a first order control on lake genesis and stability[102]; lake formation in bed depressions is favoured where ice surfaces and basal slopes are flatter[101]. However, this does not account for spatiotemporal variations in subglacial water pressure. Lake drainage occurs when the hydropotential seal is broken[103] or when water leakage from the basin produces efficient syphons[104].

Subglacial lake inventory

We constructed a new global inventory of subglacial lakes, based on lakes identified and published in the peer-review literature prior to June 2021, supplemented with 59 newly-identified lakes in Antarctica, from interrogating archived RES data collected between 2002-2019 (see Supplementary Information). The new lakes range from 170-9720 m in length (median: 1320 m) with 46 clustered in the subglacial Gamburtsev Mountains of East Antarctica beneath ice ~3000 m thick. We define a subglacial lake as any discrete water body at the base of an ice mass[25], without presuming a minimum area or depth. With this definition, lakes exist across a wide range of lengthscales[26]; from small (~1 m) water bodies in basal cavities[27] to large (> 100 km) lakes that strongly influence ice dynamics by producing flat ice surfaces[28], and from shallow (<~1 cm) water patches connected by saturated sediments[29,30] to deep (~100s m) lakes with their own internal circulation[31–35]. Although no minimum subglacial lake size is presumed, the smallest lakes in the inventory are on the order of 0.0001 km^3.

Using these criterion, we tallied 773 total lakes, including 675 from Antarctica, 64 from Greenland, 2 beneath Devon Ice Cap, 6 beneath the ice caps of Iceland, and 26 from valley glaciers (Fig. 3 and Supplementary Information). The resulting ~80% increase in the number of Antarctic subglacial lakes since the last inventory[108], largely due to new analyses of RES datasets[45,106,112], is still an order of magnitude fewer than predicted[107]. Although ~90% of inventoried lakes are beneath the Antarctic Ice Sheet, this partly reflects their larger size, making them easier to identify[108], and the bias towards Antarctic surveys.

Subglacial lake setting and behaviour

Our inventory indicates a range of lake settings and behaviours, including: isolated, stable subglacial lakes with a large size range beneath Devon Ice Cap and the interiors of Antarctica and Greenland; large (median: 0.12 km^3) but slowly (over months) cascading lake drainage beneath Antarctic ice streams; an order of magnitude smaller subglacial lakes with higher discharges (for a given lake volume) of shorter duration (days to weeks) beneath the Icelandic ice caps and ablation zone of the Greenland Ice Sheet; and small lakes (on the order of 0.0001 km^3) beneath valley glaciers that drain rapidly (<hour to days) (Figs. 3-4).

Stable lakes

Over 80% of subglacial lakes in our inventory are not active (i.e., ‘stable’ lakes in Fig. 3), which implies they are closed systems, or that inflow and outflow is approximately balanced. These predominantly RES-detected lakes occur where hydrological catchments are small[107] and basal melt rates are low or absent[55]. In Antarctica, RES-detected subglacial lakes occur beneath the warm-based interior of the ice sheet and are typically 1-5 km long, although there are many larger tectonically controlled lakes[113–115], including some >100 km long (e.g. Lake PEL[116] and Lake Vostok[28,113]). Large clusters of stable lakes occur beneath thick ice (>~3000 m) in the subglacial Gamburtsev Mountains, Dome C, the South Pole region and Ridge B beneath East Antarctica, and in the Ellsworth Subglacial Highlands beneath West Antarctica (Fig. 3b). The two RES-detected lakes beneath Devon Ice Cap are 7.0 and 8.2 km in length and occur in a similar setting to most stable lakes in Antarctica, beneath the central ice divide in bedrock troughs[55]. In Greenland, RES-detected lakes tend to occur away from the relatively flat and cold bed beneath the ice sheet's interior, and are typically <2 km long, with the largest known lake 5.9 km long[54]. Cluster of relatively large lakes occur in the East Greenland subglacial mountain chain with another cluster of smaller lakes in northern Greenland where the bed relief is subdued (Fig. 3a).

Active lakes

Active lakes in our inventory (Figs. 1, 3) have been predominantly identified, and their volumes quantified, from ice-surface elevation changes[49] and their outburst floods[117]. Because ice mechanics, ice-flow dynamics, and basal traction also influence the surface expression of lake drainage[118], lake volume can be overestimated by altimetry[119] and some ice-surface changes might not necessarily be due to subglacial lake activity[6,102,120]. Despite these caveats, our inventory indicates that active lakes generally occur closer to ice margins than stable lakes. They also have large upstream hydrological catchments and/or form in areas where meltwater is abundant, either due to frictional melting beneath ice streams and outlet glaciers (e.g., Antarctica[121]), elevated geothermal heating (e.g., Iceland[22]) and/or surface meltwater inputs (e.g., Greenland[57]).

In Antarctica, surface-elevation histories of 140 active lakes show a median volume change of ~0.12 km^3 per lake during drainage, which is an order of magnitude greater than for active lakes in Greenland, and three orders of magnitude larger than flood volume estimates of valley glaciers. This variation might partly reflect a bias in detection approaches as smaller lakes have yet to be identified in Antarctica. Most Icelandic subglacial lakes are similar in size to the active lakes in Greenland; an exception is Lake Grímsvötn, which drains up to ~5 km^3 of water because of a thick ice dam and high geothermal heat flux over a wide subglacial area[22,39].

Our inventory includes 26 valley glaciers where outbursts from small subglacial water bodies have been recorded, including 20 in the European Alps[24,40,117,122]. Transient storage in water-filled cavities is probably common to most glaciers[123–127] but their small volume makes it difficult to detect their location and differentiate outbursts from background runoff. Identified outbursts of 10^{-4} to 10^{-5} km^3 of water might therefore represent high-magnitude low-frequency events[128,129]. Although the sample size is small, glaciers with known outbursts tend to be relatively steep[40], consistent with the idea that faster sliding causes greater cavitation[124].

Patterns of subglacial lake activity

For lakes with at least one complete fill-drain cycle on record (n = 36), we identified five distinct patterns of ice-surface elevation change (Fig. 4a) based on the ratio of filling (ice surface uplift) and draining (ice surface subsidence) durations, as follows:

- Pattern 1: slow filling and rapid drainage (ratio > 1);
- Pattern 2: similar rates of filling and drainage (ratio ~1);
- Pattern 3: rapid filling and a longer period drainage (ratio < 1);
- Patterns 4 and 5: extended (multi-year) periods of quiescence, at a high stand and low stand, respectively.

Patterns 1, 3 and 4 are the most distinctive, while the difference between patterns 2 and 5 is less clear. For many lakes outside Iceland, short observational records make it difficult to determine whether the fill-drain cycles and patterns repeat, and whether they are regular and predictable[7]. Drainage of active subglacial lakes is variable[6,15,22,129,130] and does not necessarily result in complete emptying[22].

In Iceland, all lakes exhibit Pattern 1, with Grímsvötn draining every 1-10 years[22] (roughly depending on ice dam thickness[110]) (Fig. 4a). Rapid drainage of these lakes can either take the form of exponentially rising discharge, consistent with drainage via subglacial channels[39,103,131,132] and linearly rising discharge triggered by rapid subglacial lake refilling, flotation of the ice dam, or initial drainage as a sheet flood[22,109,133]. This second drainage style is thought to explain rapid discharge (<1 hour) of water from subglacial cavities[40,129].

The fill-drain patterns of active lakes in Greenland ($n = 7$) and beneath valley glaciers ($n = 26$) are not well constrained due to limited data. In Greenland, three active lakes have extended high stands (Pattern 4), which suggests an external threshold controlling lake drainage initiation[16]. However, active lakes in Greenland and beneath valley glaciers are strongly influenced by input of surface meltwater or rainfall to the bed, which can trigger drainage[41] through seasonally-modulated fill-drain cycles in smaller lakes[98,130], or late summer drainage of larger lakes[15,57]. Diurnal to seasonal drainage of water filled cavities is hypothesised to occur in response to meltwater driving unstable expansion of intervening orifices[124,134,135] allowing them to connect[136,137] and empty rapidly down subglacial channels[41,129].

In Antarctica, we observed all five drainage patterns[7], likely reflecting the range of subglacial lake sizes and their topographic, hydrological, geological and glaciological settings. Here, cascades of hydrologically-connected lakes have produced complex drainage responses[7,138]. For example, the quiescent phase of lakes characterised by Pattern 5 might be due to water capture or interception by an upstream lake, which later drains into the lower lake triggering its fill-drain response. Patterns 2 and 3 in Antarctica have been replicated by the subglacial Glacier Drainage System (GlaDS) model[7,104], which includes both distributed and efficient drainage and changes in catchment scale water pressure[139]. GlaDS suggests that most active Antarctic lakes have some outflow even during filling periods, and that small changes in pressure and drainage efficiency drive lake filling and drainage[7,104].

Lake discharge and recharge relationships

Despite uncertainty in lake volumes derived from ice-surface elevation changes[119], active subglacial lakes of Iceland, Greenland and Antarctica exhibit consistent quasi-linear relationships between mean discharge Q_m and lake volume V across drainage events (Fig. 4b), with $Q_m \propto V^b$ where b is of order unity, despite variations in lake setting, geometry and dynamics. This finding parallels the empirical Clague–Mathews relationship[140] between flood peak discharge and volume for marginal ice-dammed lakes, and is consistent with Nye's theory of lake drainage via subglacial channels, which predicts that b=1 for any set of geometrically similar lakes[141]. This suggests that drainage of active lakes in Greenland and Antarctica predominantly occurs through subglacial channels[7,142]. For a given V, Q_m is one to two orders of magnitude higher — and the flood duration proportionally shorter — for lakes in Greenland and Iceland compared with Antarctica (Fig. 4b); Antarctic lakes typically take tens of months to drain, while lakes in Greenland and Iceland drain in days to weeks. This difference is consistent with jökulhlaup theory in that the hydrologic gradient strongly influences the drainage time scale[21,141]. Steeper ice surfaces, and hence higher hydrologic gradients, in Iceland and near the Greenland Ice Sheet margin produce greater subglacial lake discharges of shorter duration than the shallower ice-surface slopes of Antarctica. Conceivably, lakes beneath steep valley glaciers might drain even faster for a given lake volume, but we lack observations to test this hypothesis.

The recharge rate of subglacial lakes also displays a consistent power-law relationship with lake volume where different lake populations have similar recharge rates (Fig. 4c). Larger lakes recharge faster than smaller lakes, indicating an underlying control on lake refilling associated directly or indirectly with lake size. Although this relationship is not fully understood, and recharge rates for smaller lakes is more uncertain as they are more difficult to observe, we suggest that larger lakes are more likely to form in larger catchments associated with greater meltwater input. A similar scaling relationship is found between the area of subaerial lakes and their catchments[143].

Subglacial lakes and ice dynamics

Observations of the influence of subglacial lake activity on ice flow are limited[10,11,13,15,90,144–146]. Most of our understanding stems from numerical models[103,147,148] and observations of subglacial water drainage from ice marginal lakes[149,150] and surface meltwater inputs to the bed[151].

Subglacial lake drainage can impact ice flow by altering basal water pressure and thus basal traction[144] (Fig. 5). The size of this impact depends on whether, and to what extent, lake discharge exceeds the hydrologic capacity of the existing subglacial drainage system. If lake discharge is relatively small and enters an efficient (high hydrologic capacity) subglacial drainage system, the ice velocity response will be limited[144] (Fig. 5). We expect these conditions in regions with significant seasonal surface melt and steep subglacial hydrologic potential, for example in Greenland and beneath valley glaciers[54,130].

Lake discharge that exceeds the hydrologic capacity of the existing subglacial drainage system will cause a transient increase in basal water pressure and enhanced basal sliding[148] (Fig. 5). Initial acceleration will be larger with a greater water pressure perturbation, for example during higher lake discharge, or in a less efficient drainage system. Once discharge falls below the drainage system's hydrologic capacity, water pressure decreases and high-pressure water drains from connected areas of the bed, increasing basal traction and reducing sliding over a large area[144]. This behaviour is expected for lake drainages beneath relatively thin ice with steeper hydrologic potential gradients, where subglacial channels are more likely to form and take longer to close due to lower creep closure rates. For example, eight days after the 1996 drainage of Lake Grímsvötn began, downstream ice velocity had increased by 200% over an 8 km wide area around the subglacial flood path[144]. This increase was followed by a 50% deceleration in ice flow, which did not fully recover for 4 years[145]. A similar pattern on a shorter timescale has been observed[16] in west Greenland, where, in the month following drainage of a subglacial lake 6 km from the terminus of Isunnguata Sermia, mean ice velocity reduced by ~25%.

Subglacial lake drainages beneath Thwaites Glacier, West Antarctica produced muted (<3%) ice-flow accelerations of several-days[146]. During a 2012 drainage event, a 2% increase in velocity was followed by a ~3% deceleration over 6 months. In East Antarctica, drainage of two lakes beneath Byrd Glacier with a mean discharge of 70 $m^3 s^{-1}$ increased ice flow by up to 10% over the 75 km long glacier trunk between December 2005 and February 2007[11]. Five years of continuous Global Positioning System data on Whillans and Mercer ice streams in West Antarctica revealed net ice-flow enhancement associated with a cascading lake drainage event[14]. This enhancement comprised three episodic ice flow accelerations of up to 4% over the two-year duration of flow enhancement but no subsequent slow-down to below the pre-drainage event ice velocity. Multi-year but more muted ice flow enhancement compared to observations in Iceland[144] are consistent with lower subglacial lake discharges of longer duration in Antarctica (Fig. 4b). As Antarctic ice streams are typically characterised by abundant subglacial water and saturated sediments[152–154] lake drainages may have a limited additional impact on basal friction. Subdued deceleration on the falling limb of the lake drainage hydrograph is possible for several reasons. First, although theoretically possible[7,142], formation of low-pressure channels is less likely due to shallow hydrologic potential gradients, which limit the generation of turbulent heat, and heat loss to colder overlying ice. Second, any low-pressure channels which form during peak discharge might have limited extent[142] and are likely to be rapidly shut down once discharge wanes, limiting their ability to capture high-pressure water from adjacent connected areas.

The net long-term impact of subglacial lakes on ice velocity depends on the balance of reduced motion (compared to ice motion in the absence of lakes) during lake filling[14], enhanced motion during lake drainage, and reduced motion following the development of efficient downstream drainage, which might in some cases go below long-term average values. These effects depend on evolving and interrelated parameters such as lake filling rate, lake discharge, ice thickness and temperature, subglacial hydrologic gradient, and the hydrologic capacity of existing subglacial drainage. A universal association between subglacial lake activity and ice motion therefore seems unlikely; indeed, while one study[13] suggests a net long-term reduction in ice motion can result from lake filling and drainage, another[14] found that a two-year period of lake filling, followed by a two-year period of lake drainage resulted in a positive velocity anomaly compared to long-term average.

Landscape impact

Subglacial lake drainages can erode, transport and deposit large volumes of sediment sub-, en-, and proglacially. Observations from contemporary subglacial lake outburst floods show evidence of mechanical erosion of subglacial sediments[155–157], rapid deposition of *eskers* and fracture fills within the ice mass[158,159], the construction of large outwash plains[15,160–163] and proglacial debris flows on steeper slopes[41,129]. In Iceland, repeated outburst floods are thought to dominate sediment supply to the proglacial foreland and contribute to the formation of substantial sandurs[164,165]. Former subglacial lake drainage event(s) have been inferred from large (10^2-10^3 m wide) palaeo-channels cut into the bed[166–172], which can funnel ice flow and influence ice dynamics[173]. For example, estimated peak discharge is 1.6-2.2 x 10^6 $m^3 s^{-1}$ for the Labyrinth, an outburst flood landscape in the McMurdo Dry Valleys, Antarctica[167], which is ~2 orders of magnitude greater than the largest subglacial lake floods observed today.

Sediment erosion and transport during lake drainage is thought to be roughly proportional to discharge[161,174], although modulated by substrate, sediment availability, and the flood route and hydrograph shape[157,175]. In particular, rapidly-rising (linear increase in discharge) subglacial lake outburst floods in Iceland cause significant landscape modification[161]. For example, the 1996 jökulhlaups from Grímsvötn drained 3.2 km^3 of water within 40 hours, had a peak discharge of 4 x 10^4 m^3 s^{-1}, and flooded the entire outwash plain[22]. The sediment yield was ~1.8 x 10^8 m^3, equating to 0.3 m (65,700 m ka^{-1}) of erosion across the glacier bed impacted by floodwaters[164,176,177]. This erosion compares to average glacial erosion rates for Vatnajökull Ice Cap of ~0.32 m ka^{-1} [178].

Similar rapid drainages from lakes beneath valley glaciers[41,122] (<hours to days) and the Greenland Ice Sheet[16] (<1 month) also result in substantial geomorphic change. Small outburst floods caused by release of subglacial water stored in cavities beneath South Tahoma Glacier on Mount Rainier, Washington, typically transform into debris flows as they incorporate proglacial sediment on the valley slopes[117,129,179]. Between 1967 and 1994 at least 23 outburst events have occurred, resulting in significant incision of sediment and stagnant ice in the upper catchment (>20 mm a^{-1}), and aggradation of up to 10^7 m^3 sediment in the downstream valley[179]. The 2015 outburst of a small (<1 km^2) subglacial lake close to the margin of Isunguata Sermia, western Greenland, flooded the foreland, aggrading the proglacial channel by up to 8 m close to the outlet.

The geomorphic impact of Antarctic subglacial lake drainages is constrained by large bedrock[168,169,171] palaeo-channels, active[180] and palaeo[181] sediment channels, and eroded or restricted landform growth at the grounding line (e.g. grounding zone wedges)[181]. Larger Antarctic subglacial lakes (Fig. 3b), with longer duration drainage might enable the transport of more sediment if there is an abundant supply[182]. However, gradual leakage of water from Antarctic lakes[8] and the lower mean discharge (Fig. 4b) suggest they might be less effective geomorphic agents than lakes in other settings.

Subglacial ecosystems

Subglacial lacustrine systems store, transform and export carbon and nutrients[9,183]. Although these fluxes are poorly understood due to limited direct observations, dissolved elements and sediments in subglacial discharge and any turbulent mixing resulting from discharge dynamics, can enhance primary productivity in downstream environments such as proglacial lakes, fjords and the polar oceans[184]. The hydrological and glaciological context of subglacial lakes influence *in situ* geochemical conditions which, in turn, control the metabolic regime and distinct genomic adaptations of resident microorganisms. To date only four active subglacial lakes have been directly sampled for microbial analyses[1,63,66,67] (Fig. 3). However, these limited samples retrieved directly from subglacial lake water and sediments confirm the presence of active microbial communities[185].

Subglacial lacustrine ecosystems (Fig. 6) must contend with permanent darkness, high pressures and low temperatures. In the case of hypersaline lakes, cells must also manage salt stress. The absence of sunlight requires that microorganisms harness energy from thermodynamically favourable and predictable chemical reactions known as *"redox" reactions*[186] with primary production via *chemosynthesis*[1,2,63,187,188]. A wide range of materials provide electrons for reduction in the subglacial setting, including geological sources such as bedrock minerals, either *in situ* or scoured during lake drainage and refill, reduced compounds such as sulphur from geothermal fluids, or biological sources such as the by-product of microbial sulphate reduction or *methanogenesis*. Organic matter might be transported from the surface or available from 'legacy' ecosystems overridden by advancing ice sheets including marine or terrestrial *necromass* as well as any labile organic matter in underlying sediments[189,190]. Any available oxygen in the subglacial environment would be rapidly consumed through microbial oxidation of reduced substrate, including organic matter or inorganic compounds such as sulphide, ammonia, methane or Fe(II). Given sufficient electron donors and no new input of oxygen, subglacial systems will be driven to anoxia, conditions in which some microorganisms can respire using diverse alternate electron acceptors, with predictably decreasing energetic yield. Evidence for iron reducers, denitrifiers, sulphate reducers and methanogens, which respire Fe(III), nitrate, sulphate and carbon dioxide, respectively, have all been observed in subglacial lake settings[1,191–193].

Active lakes along continental margins, such as Whillans Subglacial Lake (Fig 6a) may accumulate solute-rich porewaters generated by upstream basal melt. The formation of steep chemical, physical and biological gradients at lake water-sediment interfaces can influence microbial abundance and productivity[194]. Accumulated solutes and recycled organic matter can provide nutrients for energy-yielding metabolisms and cellular biosynthesis. Data from Whillans Subglacial Lake (Fig 6a), indicate that ammonium ions are an important energy source for biosynthesis[2,195], and taxa related to N-cycling microorganisms, for example, the betaproteobacterium "*Candidatus* Nitrotoga arctica", are abundant[1,196]. This group is known to mediate the oxidation of nitrite to nitrate, an important step in *nitrification*[197]. Sediment-water interfaces, where ions diffuse upwards into the water column[1,198], create a niche for enhanced microbial activity and higher rates of dark carbon fixation[3]. Transitioning into lake sediments, microbially-mediated methane[191] and sulphur oxidation[192] are key processes.

Active subglacial lakes below Vatnajökull Ice Cap, Iceland (Fig 6b), provide a redox gradient of oxygenated glacial melt and reducing geothermal fluid, which can also support *chemolithotrophic* communities[188]. Microbial assemblages in western Skaftá Lake, for example, utilize sulphide, sulphur or hydrogen as electron donors and oxygen, sulphate or CO_2 as electron acceptors[63,67]. Similarities in the microbial community between distinct lakes below Vatnajökull suggest a subsurface hydrological connectivity that can seed these transient lakes with cellular biomass and nutrients discharged in jökulhlaups[188], which ultimately impacts downstream biological communities including fishing grounds[199].

Greenland's active subglacial lakes (Fig 6c) are largely thought to be filled by the rapid injection of surface melt via moulins[57], which would provide oxygen and photosynthetically derived organic matter, supporting aerobic metabolism. This seasonal delivery could create physical turbulence, scouring legacy organic material as drainage systems expand[200]. Aerobic respiration would eventually exhaust the supply of oxygen, driving the system to anoxia as winter temperatures freeze out fresh surface melt. Although Greenland subglacial lakes have yet to be directly accessed, multiple lines of evidence suggest microbial methane production, an anaerobic process, occurs at its bed[201–203]. In fact, Greenland lakes may be quite diverse with recent evidence suggesting hypersaline or geothermally heated systems[204], with both scenarios shaping microbial communities.

Significantly less is known about the deep, closed-basin lakes under the thick (>1 km) interior of ice sheets, although they are also anticipated to host ecosystems, due to possible geothermal stirring of nutrients[31] and oxygen derived from sediments and/or the ice above. Samples of accretion ice above Lake Vostok contained 10s-100s of DNA-containing cells per ml of melt water[205] and while these numbers are low compared to Whillans Subglacial Lake, which contained ~100,000 cells in the same volume, uncontaminated samples from Lake Vostok water remain elusive[68]. Regardless, water column samples collected at a discrete depth might not be representative of water body dynamics, as subglacial lakes can be thermally unstable[3], driving internal mixing[31]. Hypersaline lakes beneath Devon Ice Cap[55] present an intriguing end-member system, where microbes must survive in high solute concentrations.

Future evolution of subglacial lakes

This Review has identified a range of subglacial lake behaviours (Fig. 7) providing a proxy for how their role might evolve in the future under changes in local conditions. This includes large stable lakes beneath ice mass interiors, slowly cascading lake drainage beneath Antarctic ice streams (Fig. 7a), faster draining smaller lakes beneath the Icelandic ice caps and ablation zone of the Greenland Ice Sheet (Fig. 7b-c), and water-filled cavities that drain rapidly beneath valley glaciers (Fig. 7c). This progression coincides with steeper ice-surface slopes, thinner ice, and enhanced meltwater inputs. Similar temporal changes are expected as climate warming causes ice mass loss, recession and thinning[206,207], increased surface[208] and basal[209] (due to faster ice flow and surface melt inputs) melting, inland expansion of ablation areas[210,211], and ice acceleration, for example, due to thinning and loss of buttressing ice shelves[212,213].

In general, subglacial lakes are predicted to be less abundant beneath smaller ice masses as recession produces steeper mean surface slopes (higher hydrologic gradients) reducing the potential for hydrologic minima[102,105]. Thus, as ice masses shrink, the relative area of the bed occupied by subglacial lakes should decrease (Fig. 7). This decrease is consistent with the reduction in water volume stored in Icelandic ice-dammed lakes since the early 20th Century as their ice dams lower in response to climate warming[22] and the drainage of a subglacial lake beneath Crane Glacier, Antarctic Peninsula, due to ice-surface steepening following ice shelf collapse[12]. Warming of ~1.8°C in Greenland[214] is predicted to lead to irreversible mass loss over multi-millennia, while 2-3°C warming in Antarctica[215,216] is likely to cause substantial grounding-line retreat and the collapse of major marine drainage basins in West Antarctica[217]. Thus, ice-surface steepening due to grounding line retreat and loss of ice shelves is likely to trigger lake drainage and reduce the potential for subglacial ponding. In general, East Antarctic Ice Sheet decline is predicted to be initiated at ~6-7°C warming and will likely be dominated by the melt-elevation feedback[215,216,218]. Here, subglacial lakes are likely to remain relatively stable over multi-millennia timescales, and might even increase in number around the margin due to enhanced surface melt and its input to the bed.

Although we predict a general decline in lake abundance and total water volume as large ice masses shrink, spatial heterogeneity in subglacial lake distribution beneath the Antarctic and Greenland ice sheets (Fig. 3) suggests this pattern is complicated by local factors including bed roughness, basal thermal regime and geothermal heat flux[107] (Fig. 7). Rough beds can promote cavitation[125], and have more topographic depressions for subglacial water storage. For example, lakes are clustered within the Ellsworth Subglacial Highlands[112] and subglacial

Gamburtsev Mountains[45] in Antarctica. These lakes, particularly associated with deep tectonic troughs (e.g. Lake Vostok)[114], are more likely to withstand ice sheet changes. Basal thermal regime controls the availability of water to form lakes and will change in response to ice sheet evolution[219] and reorganisation of water or ice flow[220–222]. Currently, there are abundant large, stable lakes beneath the warm interior of Antarctica whereas the near freezing interior of Greenland is largely devoid of lakes[54] (Fig. 3). Increases in the aerial extent and intensity of basal melt beneath the Greenland Ice Sheet[209] could facilitate inland expansion of new subglacial lakes. Any increase in saturated sediments would facilitate enhanced rock-water interactions liberating solutes for microbial processes. Thinning of ice overlying subglacial magma systems – such as those beneath the West Antarctic Ice Sheet[223], Iceland[224] and Chile[225] – could stimulate volcanic activity[226–228], resulting in more numerous and active lakes.

Mountain glaciers are undergoing widespread recession and thinning in response to climate warming[229]. However, the link between climate and subglacial storage beneath these smaller ice masses is poorly constrained and likely to be strongly influenced by local factors. For example, debris covered glaciers are undergoing a reduction in surface gradient caused by a down-glacier increase in debris thickness that focuses the highest rates of surface lowering in the mid-ablation zone[230]. This change in gradient might enhance storage of subglacial water in these glaciers. The storage capacity of subglacial cavities[125] will also control the distribution and extent of ponding at the bed and is likely to be a key mechanism beneath mountain glaciers (Fig. 7c). Cavitation is expected to be greatest on rough and steep beds and where basal sliding is high[124,134]. Thus, steep valley glaciers on rough beds could have an abundance of small, seasonally draining subglacial lakes[40] which could become more common as melt inputs increase basal sliding. Finally, the susceptibility of a glacier to surging has been linked to increased basal water storage beneath longer (and shallower) glaciers and between cold-dry and warm-temperate climate extremes[231].

Larger, stable lakes tend to be located beneath or near ice sheet divides where surface slopes are generally low while hydrologically active lakes occur closer to ice margins where the hydrologic gradient is steeper (Fig. 3). Hence an evolution from ice sheet centre to margin dictates lake formation and associated hydrological processes. Ice masses with steeper hydrologic gradients (Fig. 7a-b), produce higher subglacial lake discharges of shorter duration (Fig. 3b)[21,141] and ice surface melt and rainfall inputs to the bed can trigger[122,129] or modulate drainage[57,130]. For example, outburst floods from beneath South Tahoma Glacier usually occur during hot or rainy weather in summer or early autumn, and the probability of an outburst increases with temperature[129]. As surface melt intensifies and expands inland[210] and where ice-margin retreat and ice shelf loss causes hydrologic gradients to steepen, we expect more vigorous lake activity over a greater proportion of the bed (Fig. 7). In particular, ablation zone expansion could create new drainage pathways, facilitating the drainage of formerly isolated lakes beneath ice mass interiors, such as Greenland[54]. Although subglacial lakes are currently isolated from surface processes in Antarctica, recent evidence of water penetrating to the bed of grounded ice in the Peninsula[232] hints at a future with increasing coupling between supraglacial and basal hydrology near the grounding line as surface melt intensifies[210]. Atmospheric warming of ~3°C could trigger widespread collapse of large ice shelves fringing Antarctica[216,218] resulting in steepening of ice-surface slopes[12]. The stability of Antarctic ice shelves is therefore likely to play a key role in controlling any shift to more rapid lake drainage.

Large melt inputs into a subglacial lake can trigger flotation of the ice dam, causing a sheet flood with a rapidly rising discharge[22] and mobilisation of large volumes[22] of sediment[164,176,177]. These catastrophic drainages might become more frequent with large and rapid surface melt and rainfall inputs[233] and ice dam thinning, providing a potential hazard to downstream populations and infrastructure in glaciated mountain regions (Fig. 7c). The increased erosive capacity may also (partially) remove sediment deposits contained within lakes reducing their potential as climate archives. The link between deglaciation and drainage periodicity is less clear. In Iceland periodicity has been related to ice dam thickness[110]. However, there is no clear difference in drainage periodicity between lakes in Iceland and Antarctica[7], which is supported by the consistent power-law relationship between recharge rate and lake size in different settings (Fig. 4c), suggesting a more complex relationship.

This conceptual model allows us to consider how future evolution of subglacial lake drainage (Fig. 7) will impact the environment and ice dynamics. Increased lake activity is likely to enhance the hydrological and biogeochemical connectivity between lakes and their surroundings[188] locally enhancing transport of sediment, solute and nutrients to downstream ecosystems[9,183] and water across the grounding line of marine-terminating glaciers[6]. The regional impact of lakes drainages on ecosystems is likely to shift through time as drainage direction is highly sensitive to small changes in ice sheet geometry[105,234]. Increased routing of water through lakes coupled with steepening ice-surface slopes will impact melt-refreeze patterns at the ice-water interface potentially disrupting lake stratification and circulation patterns, with implications for the lake ecosystem and sediment deposition[1]. Enhanced nutrient mixing might promote microbial productivity throughout the water column, however large discharge of sediments could reduce light penetration in proglacial waters inhibiting photosynthetic production. Large, episodic surface meltwater inputs into subglacial lakes[57] [129] provide a supply of oxidants, sediment, microbes and labile organic matter, which might seasonally enhance oxic processes (Fig. 6c). Conversely, scoured beds, reduced time for rock-water interactions and dilution by supraglacial meltwaters could inhibit some subglacial biogeochemical activity, but the overall impact is uncertain because we have yet to access and sample the full range of lake environments. Increased discharge of subglacial lake water at marine terminating glaciers or ice streams can modify freshwater budgets and nutrient supply within sub-ice-shelf cavities and the wider ocean[6,21]. This pattern will likely be modulated by the environment into which the water discharges and circulation in the sub-ice shelf cavity or fjord.

Subglacial lake drainage across grounding lines can enhance plume-driven frontal ablation[235–237], impacting ice margin/ shelf stability[6,20]. Embayments at subglacial lake outflow points[6], and surface depression and crevassing of ice above the grounding line following the 2003 drainage of Subglacial Lake Engelhardt, West Antarctica[20] demonstrate the potential of lake drainage events to enhance frontal ablation. An expanding ablation zone will increase the chances of lake drainage entering an existing, efficient subglacial drainage system[144] and thus having a limited impact on ice dynamics. However, higher discharge floods of shorter duration (Fig. 4b) are more likely to exceed the existing downstream hydrologic capacity, resulting in large initial ice-flow enhancements[144], followed by a reduction in ice flow as channels develop and discharge falls below the system's hydrologic capacity (Fig. 7)[15,145]. More extensive and long-lived efficient subglacial drainage will increase the probability that the ‘fill-drain’ cycle of a subglacial lake causes net reduction in ice flow.

Outlook

We have presented a new global inventory of 773 subglacial lakes: 675 in Antarctica, 64 in Greenland, 2 under Devon Ice Cap, 6 in Iceland, and 26 under valley glaciers. Due to existing data availability our inventory is heavily skewed towards Antarctica (Fig. 3), yet hydrological predictions suggest there are many thousands of unobserved subglacial lakes[105–107]. Therefore, future efforts should aim to expand the identification and characterisation of lakes below valley glaciers, ice caps and in Greenland. In particular, for mountain glaciers, the sudden drainage of lakes poses a hazard to downstream populations[125,238], thus, a better understanding of water storage and drainage beneath glaciers in vulnerable areas and how the risk might change due to climate warming should be a priority. Improvements in spatial and temporal coverage and resolution of satellites[6,88,91,95], increased availability of high-resolution multi-temporal DSMs[97,239] coupled with lake detection automation[81] and machine learning[240] will likely allow these gaps to be filled, particularly for lakes that are smaller and traditionally more difficult to detect[54,58,241]. Future satellite missions, including ESA’s Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL)[88,90]and ESA’s P-band Biomass Earth Explorer[242], will help to identify and monitor long-term changes in subglacial lakes. An orbiting radar sounder could also provide unprecedented spatial and temporal coverage of Earth's cryosphere, as well as a homogenous sampling of the ice sheet at a uniform radar frequency and quality[243,244].

Another challenge is to improve our understanding of subglacial lake fill-drain cycles. Subglacial lakes exhibit diverse drainage patterns (Fig. 4a), but only 36 lakes have observations spanning at least one complete cycle; longer-term records of how they respond to changes in climate are restricted to Iceland[22] and some valley glaciers[41]. Operational, near-real-time monitoring of subglacial lake activity from polar orbiting satellites is already providing improvements in the coverage and length of observational records. Integration of remote observations and numerical modelling has potential for characterising the timing, volumes and processes associated with lake drainage and refilling. For example, application of passive seismology (Fig. 2a), which monitors acoustic vibrations caused by turbulent subglacial water flow[245], would allow for continuous monitoring of subglacial lake dynamics, and the evolving hydrologic properties[246] of water inflow and outflow. Satellite and geophysical observations can, in turn, be used to constrain and force catchment-scale numerical ice sheet models[7,247] to analyse fill-drain characteristics, and their coupling with the wider hydrological system and overlying ice. A longer-term (centennial to millennial) perspective on past lake drainages and their role in topographic evolution beneath retreating ice sheets can be gleaned from geological landform analysis and sediment records[170,181,248], and the inclusion of sediment dynamics in subglacial hydrology models[249,250].

Coupling between lake volume and ice motion is currently poorly constrained, and requires data with high temporal resolution, ideally gapless acquisition over one or more fill-drain cycles, and broad spatial coverage to quantify the downstream dynamic effect of lake discharge. Coupled subglacial hydrology and ice dynamic modelling can utilize these data to determine the primary drivers on ice motion. Efforts must focus on constraining the initial ice dynamic response and net long-term impact of subglacial lake drainages for a range of discharge magnitudes and glaciological settings. Recent (e.g. ESA's Sentinel-1 constellation) and planned (e.g., NASA-ISRO SAR (NISAR)) SAR-imaging satellite missions with high spatial resolution (2.7-22 m) and short repeat cycles (6 to 12 day) will improve the likelihood of obtaining high quality ice motion and surface topography data from image cross-correlation and (Differential) Interferometric Aperture Radar[239] even for ice masses that experience significant surface melting or snowfall. Coupling of subglacial and ice dynamics models will allow analyses of physical drivers of lake stability and future lake behaviour.

Direct access into subglacial lakes representing the range of hydrologic, dynamic and mass balance regimes is needed to understand the factors that control metabolic productivity and taxa diversity of resident microbial communities. Biogeochemical measurements from a range of subglacial conditions will inform global carbon budgets and support predictions of how climate change may alter the function of these ecosystems. Replicate samples from subglacial lakes can inform the stability of communities and pace of ecosystem change. Because discharge from subglacial lakes likely has important implications for downstream ecosystems, continuing to identify and characterize discharge points, particularly at marine-terminating systems, is critical. Advances in automated underwater vehicles, which can scan larger areas along coastal margins, particularly along underexplored grounding zones, will be required.

Drilling capabilities that enable clean, direct access into subglacial lakes are essential for advancing our understanding of resident microbial communities. Recently, hot water drills have been designed with systems that filter and irradiate melt water used in drilling[251,252]. Further development of these systems for logistical efficiency and increased automation, coupled with progress in thermal probe technologies[253] that enable *in situ* measurements and acquisition of samples for microbial analysis[254,255], will be crucial for exploring deep subglacial lakes[253,255].

Geophysical innovations will reveal more about the physical properties of subglacial lakes and how they change through time. Autonomous phase-sensitive radio-echo sounding (ApRES)[256–258] can determine vertical strain in the ice, gleaning information on the ice-dynamic response to lake filling and draining, and basal melt/freeze rates, providing critical input data for water circulation models. Next-generation full-waveform inversion techniques for interpreting active-source seismic observations[259] provide more precise constraints on the structure of subglacial water systems, particularly for regions with thin water cavities and/or sediment layers[260]. EM approaches provide constraints on the pore-water properties of water-saturated subglacial sediment packages and the salinity of lake waters. Developments in time-lapse geophysical monitoring, innovations in miniaturisation, autonomy, cost reduction, and power savings for geophysical sensors[70], as well as integration of different geophysical approaches (e.g. EM and seismic exploration to derive lake salinity[84,261]) with numerical modelling of lake hydrology[31] will refine the spatial and temporal resolution of our understanding of subglacial lakes. Together, these developments will provide a more holistic understanding of how subglacial lakes interact with the wider hydrological system, including poorly resolved components such as the flow of water within sediments and rocks[262].

Summary

The storage of water under ice masses is widespread and occurs in a range of settings[26] and climatic regimes. This diversity has resulted in a wide spectrum of subglacial lake environments, behaviours and impacts. Our global inventory of 773 lakes suggests this diversity is related to the characteristics of overlying ice masses and the topography and material of the ice bed. Grounding-line retreat[215] and ice shelf loss of the West Antarctica Ice Sheet[216,218] may result in fewer and smaller lakes that drain more rapidly. As melt intensifies and expands further inland due to climate warming (e.g., in Greenland[208]) more subglacial lakes might become coupled to surface melt and rainfall inputs, increasing the number of active lakes and the potential for catastrophic drainages. Beneath small ice caps and valley glaciers data on subglacial lakes is limited (Fig. 3) and the impact of local controls (e.g., bed roughness) and glacial processes (e.g. debris covered glaciers) is likely to result in significant variations in their response to warming.

Increased lake activity will drive large initial ice-flow enhancements followed by a reduction in ice flow as channels develop and discharge falls below the system's hydrologic capacity. More extensive and long-lived efficient subglacial drainage will increase the probability that a fill-drain cycle of a subglacial lake will lead to a net reduction in ice flow. As hydrological connections are made between lakes, their subglacial surroundings, and the ice surface, fluxes of sediment, solute and nutrients will be temporarily stored and then released downstream, modulating the nourishment of downstream subglacial and proglacial ecosystems and providing conditions for both aerobic and anoxic processes. The future of subglacial lake investigation is likely to be driven by innovations in geophysical techniques and drilling technologies, and advances in our ability to monitor subglacial lake activity and ice motion in near-real-time from satellites and *in situ* instrumentation. Integrated programmes that bring together complimentary techniques and numerical modelling are likely to lead the way in advancing our understanding of the current and future role of subglacial lakes.

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Author Contributions:

SJL led the project and assembled the authorship team. SJL produced the global subglacial lake inventory with input from all authors. YL, RJS and KW identified the additional new Antarctic subglacial lakes included in the global inventory and wrote the Supplementary

Materials section. The section on lake discharge-recharge relationships came from discussions between SJL, FN and AJS. KW produced Figure 1; SJL produced Figures 3, 4 and 5, with help from FN and AJS; JM produced Figure 6; AR and SJL produced Figure 7; and MS, HAF and AR contributed Figure 2. All authors contributed to writing and editing of the manuscript prior to submission.

Competing Interests:

The authors declare no competing interests.

Glossary

Grounding line. *The boundary where a grounded glacier becomes a floating ice shelf.*

Basal hydrologic potential. *Total head determined by bed topography, weight of the overlying ice, and basal drainage characteristics.*

Jökulhlaup. *Glacial outburst flood from a subglacial or proglacial lake.*

Radio-echo sounding. *A radar technique used to measure the internal structure, ice thickness, bed topography and water content of ice masses.*

Equilibrium Line Altitude. *The elevation at which the accumulation and ablation of ice are in balance over a given time period (typically, one year).*

Esker. *A slightly sinuous ridge of glaciofluvial sediments (e.g. gravels) that record the former drainage of meltwater under, in or on top of ice masses.*

Cold based ice. *Ice below freezing at the ice-bed interface and thus frozen to the underlying substrate*

Redox reactions. *chemical reactions where a molecule becomes reduced an another becomes oxidized.*

Chemosynthesis. *the fixation of single carbon molecules into organic biomass using energy from the oxidation of inorganic electron donors.*

Methanogenesis. *a metabolic process that yields energy for microbial growth while releasing methane.*

Necromass. *organic material consisting of or derived from dead organsims*

Nitrification. *the oxidation of reduced nitrogen compounds to nitrite or nitrate.*

Chemolithotrophic. *the metabolic oxidation of inorganic compounds to yield energy and fix single-carbon compounds into organic biomass*

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Figures

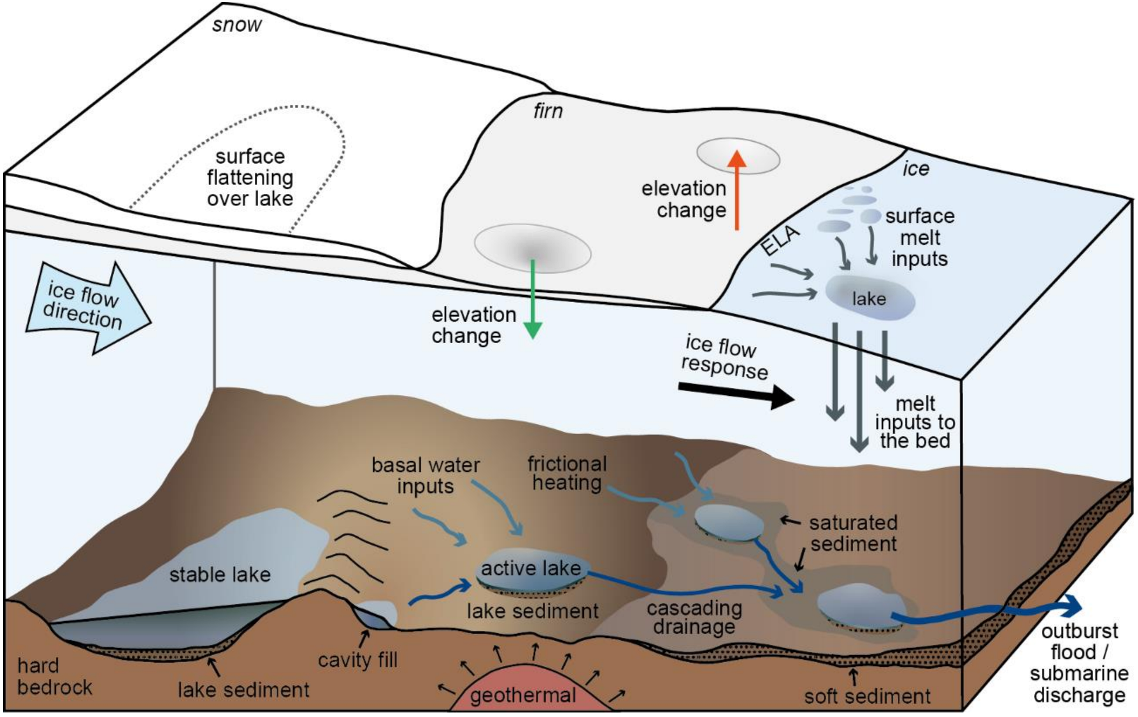

Figure 1. Different settings of subglacial lakes and their links with other parts of the hydrological system of an ice sheet or a glacier. Lakes can range from stable systems trapped in topographic (and hydrologic potential) depressions towards the interior of ice masses to water bodies in small cavities and active lakes closer to the ice margin that periodically drain downstream. Active lakes often form in regions with enhanced frictional, geothermal or surface melt inputs. Mechanical coupling between subglacial lakes and the overlying ice can cause flattening of the ice surface (especially over large lakes), localised changes in ice-surface elevation in response to lake drainage (elevation decrease) and filling (elevation increase), and transient variations in ice flow in response to lake drainages. ELA = Equilibrium Line Altitude.

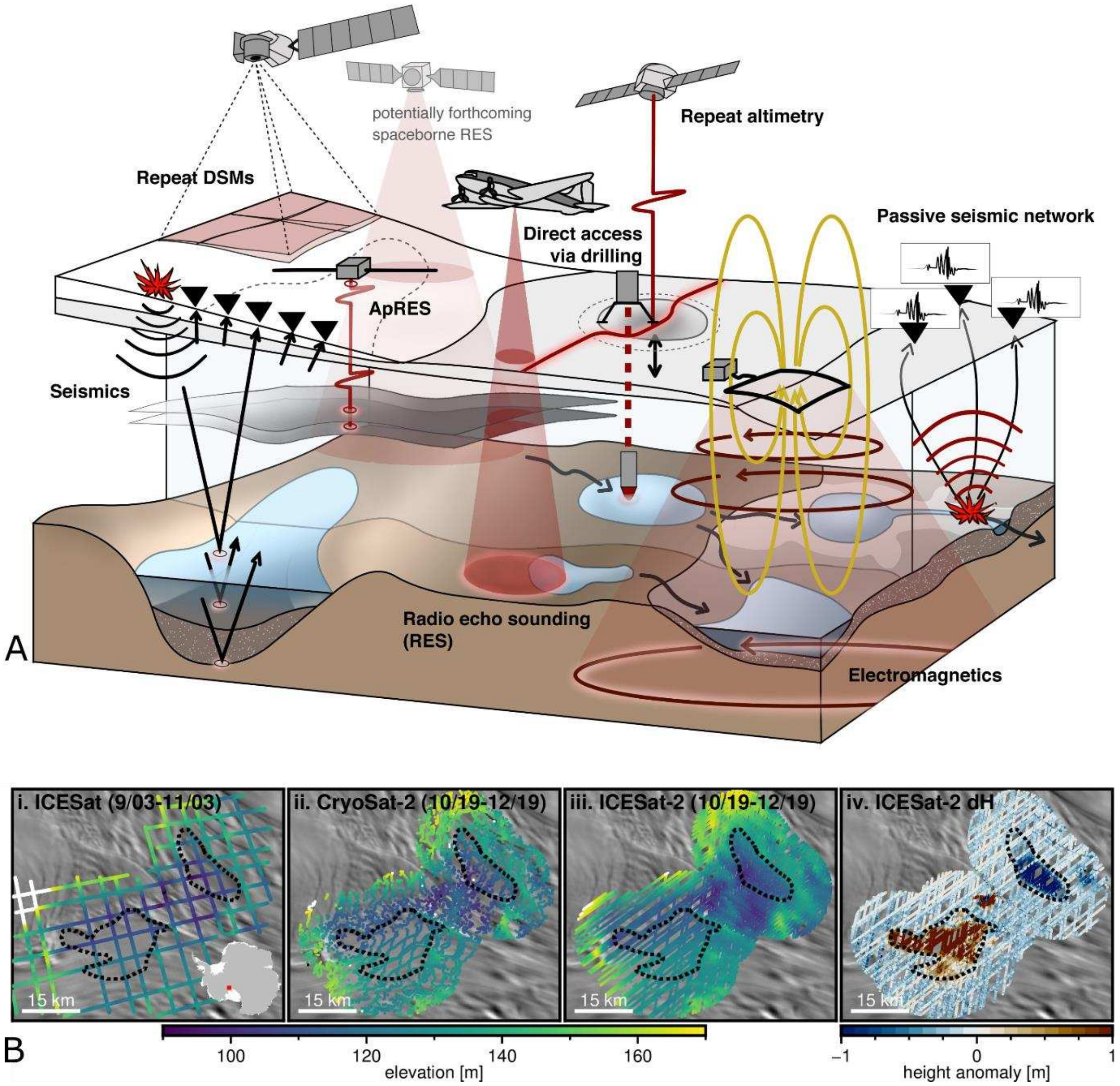

Figure 2. Recent advances and future potential for investigating subglacial lake dynamics. A. Schematic of the range of different geophysical techniques and satellites for identifying subglacial lakes, probing their environment and monitoring their dynamics. B. Comparison between altimetry coverage of active subglacial lakes in Antarctica. Ice surface elevation measurements for three months of (i) ICESat global Antarctic and Greenland ice sheet altimetry (GLA12), (ii) CryoSat-2 synthetic aperture radar interferometric (SARIn) mode, and (iii) ICESat-2 land ice height (ATL06) data coverage over Conway Subglacial Lake and Mercer Subglacial Lake, West Antarctica. Inset map shows location of panels in Antarctica. (iv) ICESat-2 ATL06-derived ice-surface height anomaly for May 2019. Figure adapted from Siegfried & Fricker (2021)[92].

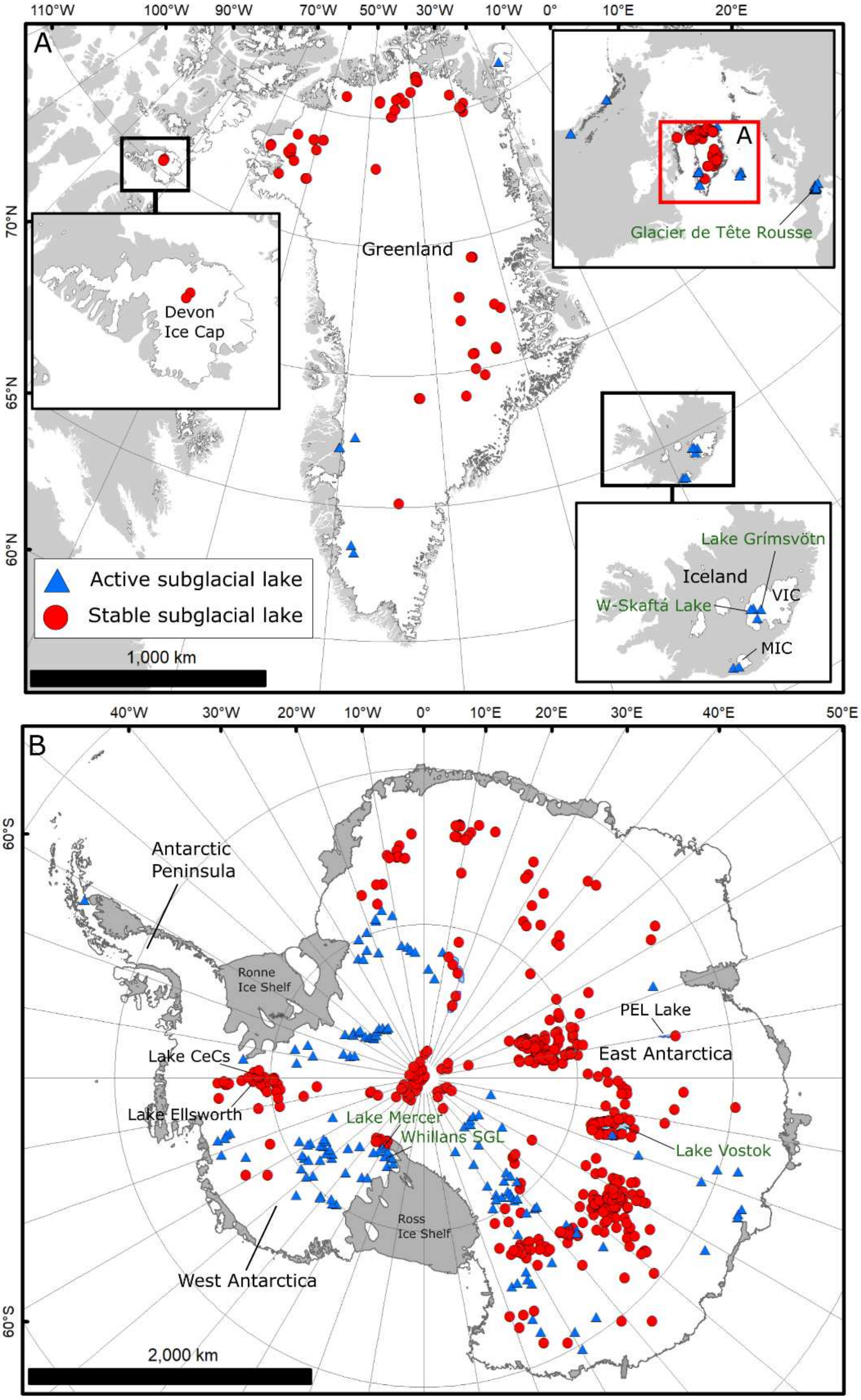

Figure 3. Global inventory of subglacial lakes. Red circles represent stable lakes identified from RES and blue triangles represent active lakes that have been observed to drain at least once. The extent of larger lakes (e.g. lakes PEL and Lake Vostok) are defined by blue polygons. VIC = Vatnajökull Ice Cap; MIC = Mýrdalsjökull Ice Cap. SGL = subglacial lake. Lakes in green have been accessed and cleanly sampled with the exception of Glacier de Tête Rousse, which was monitored using boreholes (water level) and sonar (cavity geometry), and Lake Vostok. Top-right inset of subglacial lakes identified in the northern Hemisphere shows the location of A (red box).

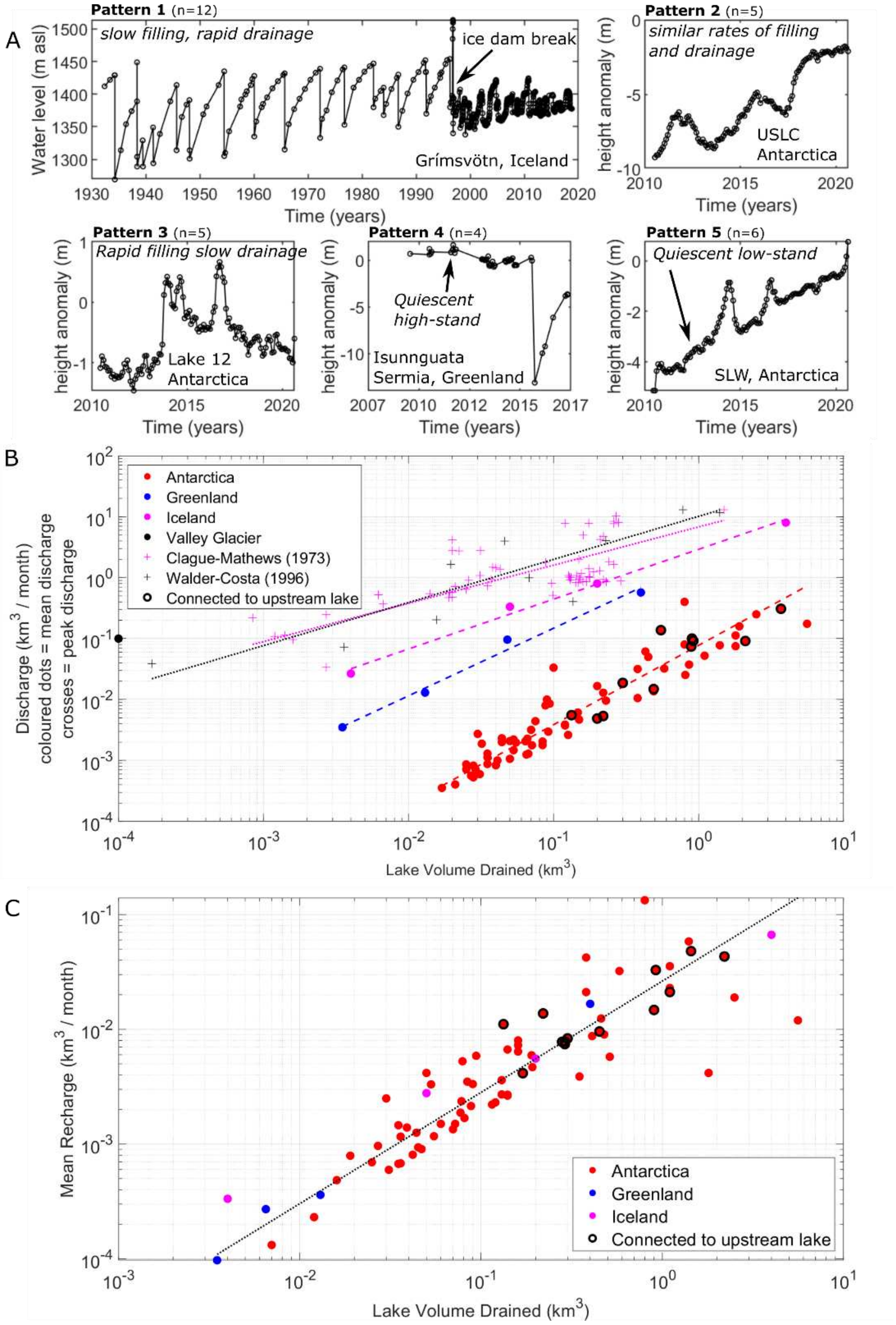

Figure 4. Fill-drain cycles and the relationship between lake volume and recharge/discharge. A. Examples of different fill-drain patterns of subglacial lakes identified from ice-surface elevation changes. This is based on lakes with at least one complete fill-drain cycle. USLC = Upper Subglacial Lake Conway; SLW = Whillans Subglacial Lake. B. Mean water discharge versus total water volume drained, for drainage events from subglacial lakes and ice-marginal lakes. Dashed lines plot orthogonal distance regression fits for different lake populations. The volume of water drained from each subglacial lake has been derived from ice-surface elevation change (see main text for caveats with using this method). Crosses represent data for ice-marginal lakes draining through subglacial channels[140,263]; the respective discharge values are peak discharges. Black outlines highlight drainage events fed by the drainage of an upstream subglacial lake. C. Mean recharge rate of different subglacial lakes plotted against lake volume change, as estimated from ice-surface elevation change (dashed line = orthogonal distance regression).

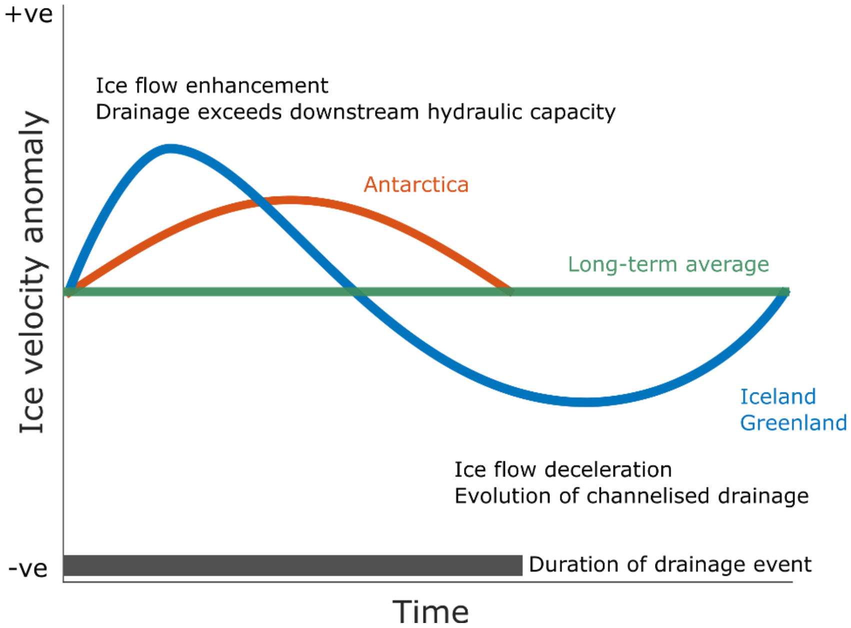

Figure 5. Conceptual model of the influence of subglacial lake activity on ice flow. For a given subglacial lake drainage event, the ice-flow response will depend on whether, and to what extent, lake discharge exceeds the hydrologic capacity of the existing subglacial drainage system. Where discharge is low and the lake drains into a pre-existing channel the ice-flow response is likely to be limited (green line). Drainage that exceeds the downstream hydrologic capacity (red and blue lines) will result in ice-flow acceleration. This acceleration might be followed by a subsequent slowdown (blue line) if water pressure in the main channel reduces and high-pressure water drains from connected areas of the ice bed.

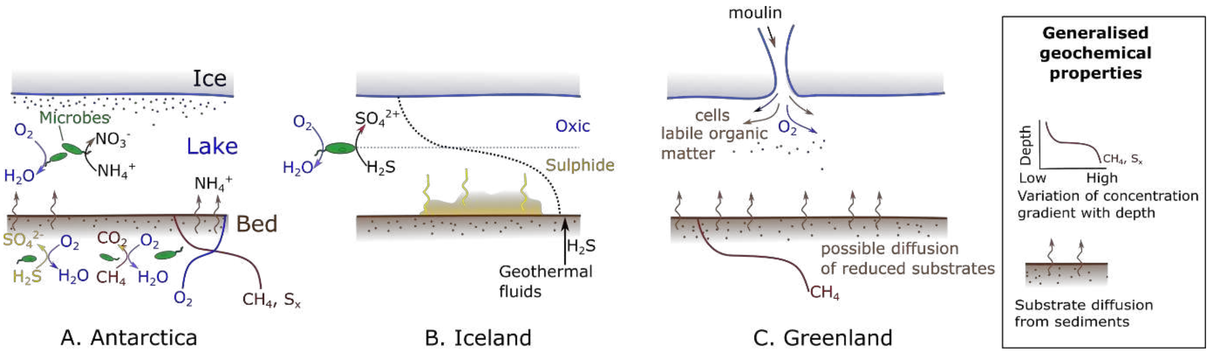

Figure 6. Generalized examples of microbial redox reactions across a range of lake settings. In the absence of sunlight, these systems derive primary production via chemosynthesis. Solute-rich porewaters deliver nutrients from the lake catchment, while sediment ions diffuse upward at the sediment-water interface. In sediments, redox transitions are influenced by oxygen availability and penetration with depth and microbial metabolic groups shift accordingly. We highlight three example lake settings. In active Antarctic lakes such as Whillans Subglacial Lake (A), basal ice interacts with the surface water column, but, in general, these lakes lack surface connectivity, which restricts oxygen resupply and delivery of photosynthetically derived nutrients within glacial melt. Icelandice lakes formed from active hydrothermal systems under ice (B) contain chemically and thermally stratified water columns, which result from the melting of oxygenated glacial ice and the flux of sulfidic geothermal fluid. At the chemocline, sulphur oxidizing microbes dominate. In an active Greenland lake (C) recharge from surface meltwater via moulins can deliver significant volumes of supraglacial materials, including photosynthetically derived organic matter that would influence redox gradients. The inset key indicates that relative changes in concentration of a particular substrate.

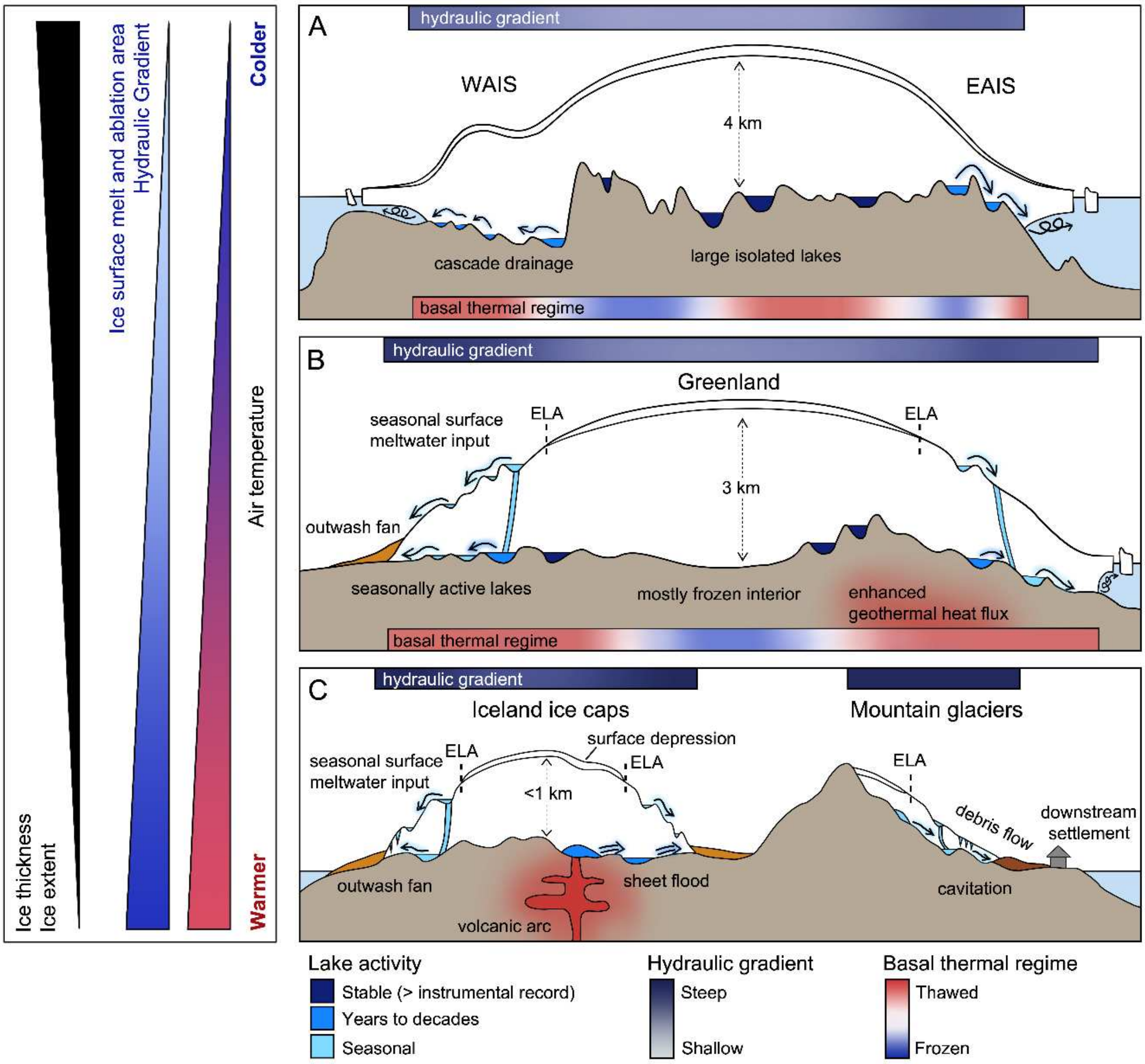

Figure 7. Space-time substitution using spatial variations in the behaviour of subglacial lakes beneath modern ice masses to assess the impacts of climate warming on their future distribution, geometry and activity. A-C are conceptual models of the hydrological systems of Antarctica (A), Greenland (B) and smaller ice masses such as ice cap and valley glaciers (C). Antarctica is dominated by very large stable lakes close to ice divides with active lakes that drain slowly (months to years) tending to occur beneath ice streams closer to the ice margin. Greenland is largely devoid of lakes in the near-frozen interior. Stable lakes are typically found above the ELA, with active lakes, recharged by surface water, found at or below the ELA and associated with higher discharges than Antarctica (draining in days to weeks). Subglacial lake discharges are similar in Iceland (days to weeks), with lakes influenced by subglacial volcanism and occasionally experiencing large sheet floods due to rapid lake refilling. Valley glaciers are associated with small lakes that can drain rapidly (<hour to days) and are modulated by surface melt and rainfall inputs. Note that the space aspect has large gaps (e.g., Antarctica is much larger than Greenland, and Greenland is much larger than the ice caps of Iceland) and little is known about how changes will manifest as ice masses shrink. As climate warms and ice sheets recede and thin, surface slopes steepen in response to ice-shelf loss and grounding-line retreat and surface melt intensifies and expands, we predict that the size of subglacial lakes and their relative coverage of the bed will generally decrease beneath the Greenland and West Antarctic ice sheets (although modulated by factors such as bed roughness and heat flux) but that they will become more active. Beneath smaller ice masses (e.g. valley glaciers) changes in lake abundance will be strongly controlled by local factors. Warming is likely to enhance the potential for surface coupling (e.g. melt and rainfall inputs), resulting in higher overall discharges of shorter duration, and more frequent sheet

floods. The reduction in ice overburden pressure might also stimulate volcanic activity, resulting in enhanced basal melting and lake formation. ELA = Equilibrium Line Altitude; WAIS = West Antarctic Ice Sheet; EAIS = East Antarctic Ice Sheet.