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The emerging importance of ice-marginal lakes across Greenland

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Acronyms

IML Ice-marginal lake

GLOF Glacial lake outburst flood

LGM Last Glacial Maximum

Glossary

Glacial lake outburst flood (GLOF) A flood event involving the sudden release of water from within a proglacial lake due to dam failure.

Holocene The current geological epoch, which began 11,700 years before present.

Ice-marginal lake A body of freshwater located against the margin of a glacier, ice cap or ice sheet, which commonly forms in glacially eroded depressions in topography.

Last Glacial Maximum The time period (20,000 – 26,000 years ago) during which continental ice sheets reached their maximum mass and extent during the last ice age.

Quaternary Period The most recent geological period within the Cenozoic Era, spanning the past 2.6 million years and extending to present.

Abstract

Ice-marginal lakes influence the dynamic behaviour of glaciers and ice sheets, impacting the rate at which they lose mass. In Greenland, accelerated ice loss over recent decades had led to an increase in the number of lakes bordering the ice sheet margin. This landscape evolution has sparked a growing field of research focused on quantitatively understanding the interactions between lakes and glaciers, so that ice-marginal lakes can be accounted for in models of ice sheet change. Ice loss from the Greenland Ice Sheet directly contributes to global sea level rise; understanding the drivers of this mass loss is important for accurately predicting future sea level. This article outlines recent advances in our understanding of lake–glacier interactions across Greenland during the past, present and future, and discusses key priorities for further research. We conclude by suggesting a series of activities that

28 introduce Post-16 students to relevant datasets and techniques.

29

30 **1. Introduction**

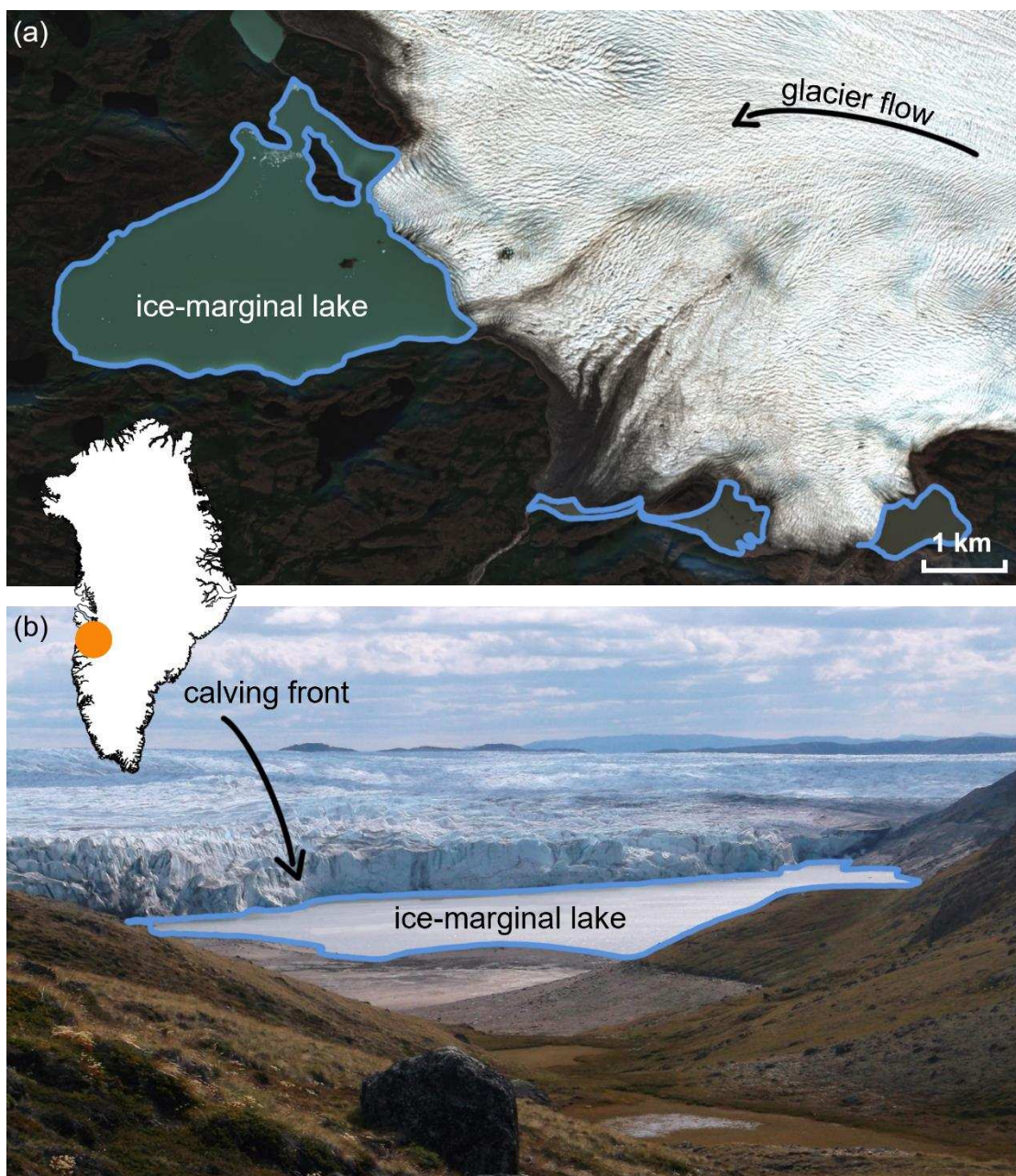
31 Roughly two-thirds of Earth's fresh water is stored in glaciers and ice sheets. These ice
32 masses are important: they impact ecosystems and ocean circulation, are an essential supply
33 of water for mountain communities and their melting directly contributes to global sea level
34 rise. Over the past 40 years, the Arctic has warmed at almost four times the global rate
35 (Rantanen et al., 2022). As a result, ice loss from the Greenland Ice Sheet has accelerated to
36 around 270 billion tonnes per year (Box et al., 2022) and is now the single greatest source of
37 sea level rise. More than 800 million people live in coastal regions worldwide, meaning that
38 accurate sea level predictions are urgently needed in order to mitigate against the impacts of
39 flooding. However, the rate of future ice loss from Greenland remains largely uncertain,
40 making it difficult to pinpoint exactly when, and by how much, sea levels will rise through the
41 coming century.

42 Approximately half of the loss of ice from Greenland happens when meltwater evaporates
43 from the ice sheet surface (The IMBIE Team, 2020). The remainder occurs via outlet glaciers,
44 which are large rivers of ice draining from the interior of the continent to the ice sheet margin.
45 Glaciers that terminate on land will melt and decay under warm air temperatures. By
46 comparison, glaciers that flow into water also lose ice through further melting caused by warm
47 water underneath and by the detachment of icebergs, a process termed 'calving'. Since the
48 end of the Little Ice Age (c. 1850), and more rapidly over recent decades, Greenland's glaciers
49 and ice caps have thinned and shrunk inland, revealing bedrock troughs in the underlying
50 topography (Mallalieu et al., 2021; Carrivick et al., 2023; Greene et al., 2024). As this
51 landscape has evolved, many of these troughs have filled with meltwater to form thousands
52 of ice-marginal lakes (IMLs – see Glossary) along the edge of the ice sheet (Figure 1).

53 Studies of glaciers elsewhere – for instance, in Iceland (Baurley et al., 2020), Alaska (Trüssel
54 et al., 2013) and the Himalaya (Zhang et al., 2019) – have shown that glaciers flowing into
55 lakes lose ice much more rapidly than those that terminate on land. IMLs are growing in both
56 number and extent around the Greenland Ice Sheet (How et al., 2021), and this trend is
57 expected to continue through the coming century as the ice sheet progressively retreats
58 (Carrivick et al., 2022). While this landscape change is likely to have significant implications
59 for the stability of the Greenland Ice Sheet, the precise effects of IMLs on Greenlandic glaciers
60 remain poorly understood and are currently missing from models of future ice sheet change.
61 Understanding how lakes alter ice dynamics is crucial for refining projections of ice sheet mass
62 loss, thereby improving our ability to predict future sea level rise. IMLs and glaciers are
63 dynamic indicators of how our world is changing. For students interested in engaging with

64 current climate research, exploring IMLs offers a chance to dive into a rapidly evolving and
65 timely subject with global significance. This topic integrates various strands of the A level/
66 Higher geography specifications, such as glaciation, geomorphology and spatial data, bridging
67 classroom learning with real-world applications while also highlighting how science tackles the
68 questions presented by climate change.

69 This article aims to review the current state of knowledge around IMLs across Greenland. With
70 a focus on lake–glacier interactions, we discuss IMLs in the past, present and future, before
71 outlining priorities and opportunities for further research. Finally, we present a number of
72 resources that can be used to explore this topic through practical activities.



73

74 **Figure 1: (a) An ice-marginal lake in west Greenland, visible in Sentinel-2 imagery**
75 **(courtesy of USGS); (b) An ice-marginal lake on the northern flank of Russell Glacier,**
76 **west Greenland.**

77

78 **2. Greenlandic ice-marginal lakes in the past**

79 Studying past environments can help us to understand the effects of climate change in the
80 future. In glaciology, evidence from the past is particularly useful because it provides insight
81 into processes that are difficult to observe, or that take place over many tens or hundreds of
82 years. Landforms created by IMLs during the Quaternary period (the past 2.6 million years)
83 are found worldwide (c.f. Carrivick and Tweed, 2013; Tweed and Carrivick, 2015; and more
84 recently e.g. Jonell et al., 2020; Panin et al., 2020; Regnéll et al., 2023). These features (such
85 as lake shorelines – see Figure 2 – perched deltas and spillways) have been used to
86 reconstruct the extents, depths and drainage patterns of past IMLs. By comparing this
87 information with evidence of glacier flow, IMLs have been found to affect the behaviour of
88 glaciers and ice sheets. For instance, by mapping and analysing landforms and sediments,
89 Perkins and Brennand (2015) identified changes in the location and water levels of lakes in
90 British Columbia, Canada, and suggested that lake–glacier interactions had resulted in active
91 glacier retreat. IMLs are also thought to have prompted the initiation of ice streams, which
92 quickly channel large volumes of ice towards the ice sheet margin and can cause rapid mass
93 loss (Stokes and Clark, 2003). This is supported by computer simulations suggesting that IMLs
94 influenced both the timing and progression of deglaciation following the Last Glacial Maximum
95 (LGM) (Utting et al., 2019; Hinck et al., 2020, 2022; Quiquet et al., 2021; Austermann et al.,
96 2022).

97 In Greenland, Holocene deglaciation has been accompanied by the formation of IMLs within
98 bedrock troughs and the arced moraine ridges deposited by mountain glaciers and ice caps
99 during the Little Ice Age (Carrivick et al., 2023). Through mapping and quantitative analysis of
100 glacial, fluvial and lacustrine (lake) geomorphology, Carrivick et al. (2017b) showed that IMLs
101 during the late Holocene (the last 4000 years) in west Greenland were temporary, often
102 interconnected, and in some cases drained episodically to produce glacial lake outburst floods
103 (GLOFs). Importantly, this predominance of meltwater in areas surrounding glaciers, ice caps
104 and ice sheets is comparable to present-day conditions, meaning that the deglacial
105 environment formed over the past 11,700 years is a useful proxy for Earth surface processes
106 taking place today. Understanding the prevalence and importance of IMLs in the past can
107 therefore be key to creating informed projections of future change.

108



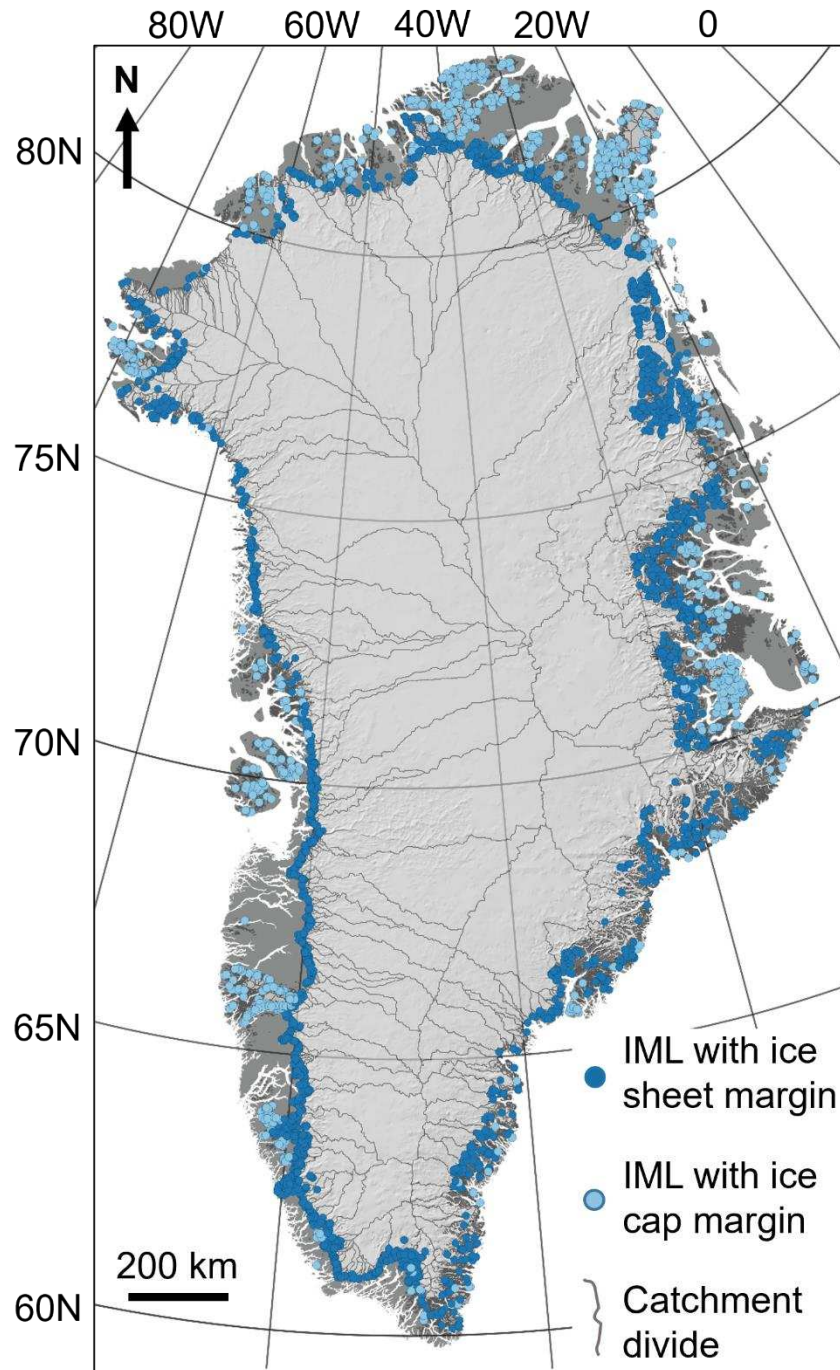
109

110 **Figure 2: Lake shorelines reveal the extent of ice-marginal lakes in the past. Photo:**
111 **Jonathan Carrivick.**

112

113 3. Ice-marginal lakes in the satellite era

114 Climate warming has accelerated the rate of ice melting in Greenland over the past four
115 decades, leading to an increase in the number of IMLs. To understand how this change affects
116 ice mass loss, it is important to know how many lakes there are, where they are, and how
117 quickly they are increasing in number and extent. A recent study (How et al., 2021) used a
118 combination of satellite imagery and topographic data to map the distribution of IMLs across
119 Greenland in 2017 (Figure 3). In total, the authors mapped 3347 lakes larger than 0.05km².
120 They found that the majority of the lakes are concentrated in the south-west and north-east,
121 where the ice sheet margin sits further inland, and that 28% of lakes are at the edges of ice
122 caps and mountain glaciers around Greenland's periphery. The lakes are typically small –
123 87% are less than 1km² – but the largest is 131km². Crucially, when compared to previous
124 work (Carrivick and Quincey, 2014), it was found that the number of IMLs in west Greenland
125 had increased by approximately 75% between 1985 and 2017. It is estimated that 10% of the
126 ice sheet margin is currently occupied by a lake (Carrivick et al., 2022); if the number and size
127 of Greenland's IMLs continue to rise, it is likely that the proportion of the ice sheet in contact
128 with a lake will also increase, perhaps exponentially.



129

130 **Figure 3: The distribution of ice-marginal lakes across Greenland, as mapped by How**
 131 **et al. (2021).**

132

133 **4. Ice-marginal lake - glacier interactions**

134 The mass of a glacier or ice sheet is determined by the overall balance between the amount
 135 of ice gained and lost. At lake-contact ice margins, the rate of ice mass loss is significantly
 136 enhanced by a series of physical interactions between the ice margin and the lake water
 137 (Figure 4; Sugiyama et al., 2011; Baurley et al., 2020; Carrivick et al., 2020; Pronk et al., 2021).
 138 Foremost, where glaciers flow into a lake and begin to float, the ice becomes destabilised,

139 fractures and breaks away into icebergs through the process of calving. This is exacerbated
140 when warm lake waters erode notches in the submerged ice front, priming it for failure. Calving
141 rates may also speed up when pressure exerted by the lake on the ice margin decreases. On
142 annual timescales, Greenland's ice margin has been observed to lose stability as ice covering
143 the lake surface melts away at the end of winter and 'unpins' the calving front. Sudden
144 fluctuations in lake water level, such as during a sudden lake drainage event (see e.g.
145 Carrivick et al., 2017a; Dømggaard et al., 2023), can similarly initiate extensive calving
146 (Mallalieu et al., 2020). Over time, if ice mass gains are outpaced by ice mass losses, the ice
147 sheet margin will retreat. Indeed, lake-terminating glaciers in south-west Greenland have been
148 retreating more quickly than their land-terminating neighbours (Mallalieu et al., 2021). This is
149 especially rapid where the underlying topography slopes inland, because recession into
150 progressively deeper water increases the thickness of ice exposed at the lake margin,
151 encouraging more ice loss and resulting in further retreat (see e.g. Sutherland et al., 2020).

152 These processes can also affect the dynamic behaviour of lake-terminating glaciers. In
153 particular, IMLs are known to enhance the speed at which a glacier flows (Sugiyama et al.,
154 2011; Pronk et al., 2021). Lake waters increase the water pressure beneath the glacier ice,
155 reducing friction and allowing the glacier to slide. As well as delivering ice to the margin more
156 quickly, this introduces a positive feedback mechanism whereby, through a process termed
157 'dynamic thinning' (Trüssel et al., 2013), the glacier stretches and thins, reducing its pressure
158 on the bed and increasing its flow velocity (Sugiyama et al., 2011). The impact of this feedback
159 is extensive: ice speed is ~25% faster at the lake- versus land-terminating margins of the
160 Greenland Ice Sheet (Carrivick et al., 2022).

161 Although numerous studies have documented these processes at glaciers elsewhere, lake-
162 ice interactions in Greenland remain largely unobserved, unquantified and poorly understood.
163 Beyond their influence on ice mass loss and sea level rise, IMLs have important societal
164 impacts. Greenland's lakes are prime locations for hydropower generation and recent years
165 have seen the approval of multiple hydroelectric projects which require accurate predictions
166 of future lake water levels. In addition, the lakes are vulnerable to GLOFs (e.g. Russell et al.,
167 2011) which pose a threat to people and infrastructure, and which have the capacity to
168 dramatically alter the landscape through erosion and deposition (Carrivick and Tweed, 2019).
169 In light of this, current research aims to better understand where IMLs will form and evolve,
170 how they interplay with ice dynamics, and how they will respond to climate change in the
171 future.

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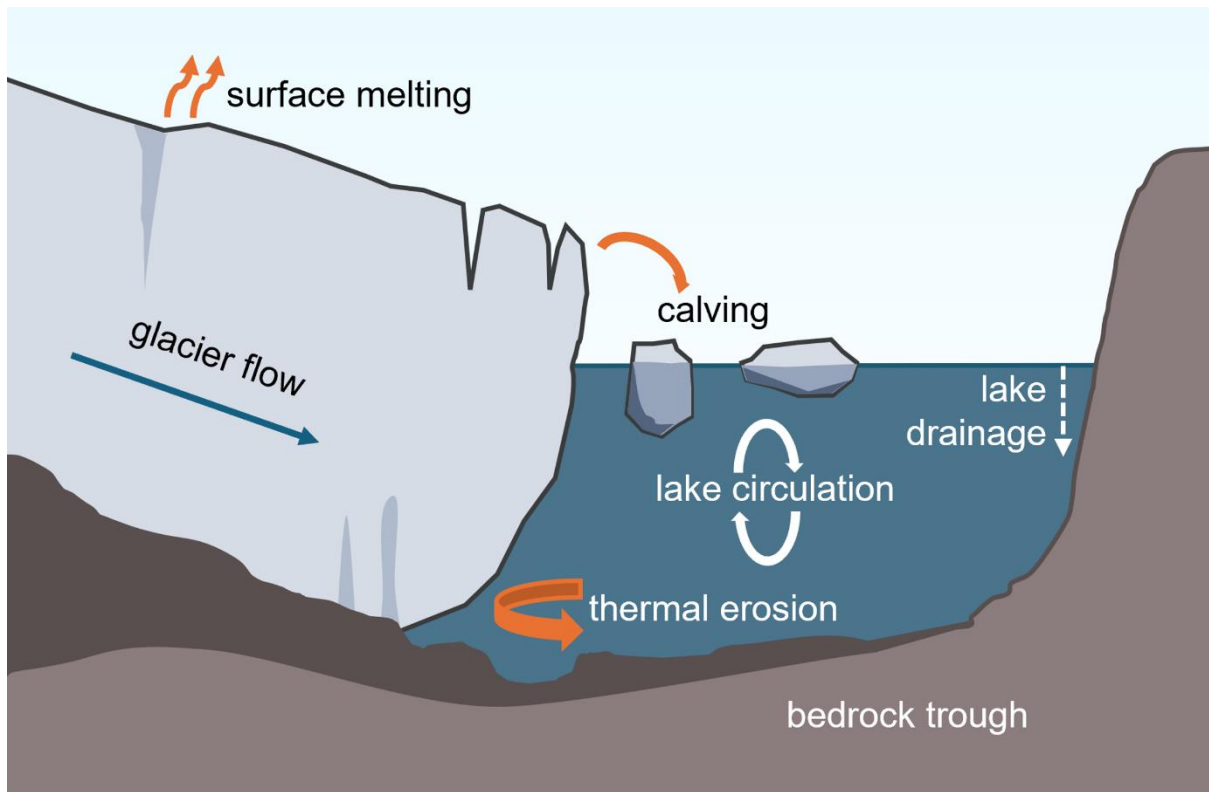


Figure 4: Key processes within an ice-marginal lake.

5. Projecting the future

Projecting how much and how quickly the Greenland Ice Sheet will lose mass in the future is important for improving predictions of global sea level rise. These predictions come from computer models of ice sheets and glaciers, which are carefully adjusted to match past environmental conditions so they can be used to estimate future changes. Numerical models represent real-world physical processes by a series of equations that are solved to understand how the system will respond under different climate scenarios. However, interactions between glaciers and IMLs are complex, meaning that the representation of feedbacks between glacier melt, IML evolution and ice dynamics remains beyond the capacity and capability of many mountain glacier and ice sheet models. As a result, IML processes (whether applied to modern or Quaternary systems) are at best poorly represented, or at worst not represented at all within modelled estimates of ice sheet change. To address this, innovative and ambitious numerical modelling of IMLs has recently gained traction (Tsutaki et al., 2019; Sutherland et al., 2020; Hinck et al., 2020, 2022; Quiquet et al., 2021; Austermann et al., 2022). Extensive work has been conducted to improve the physical basis of ice sheet models, with a particular focus on calving processes. It is easy to assume that an ice sheet model made for marine environments could be adapted and applied to lake-terminating glaciers (Sutherland et al., 2020). However, significant differences in the physical conditions of marine and freshwater environments, such as water density and water level variability (Truffer and Motyka, 2016), mean that lake-contact

195 ice margins require their own set of model conditions. The complexity of the boundary between
196 a glacier and a lake makes meeting this need a challenging task for ice sheet modellers. To
197 accurately represent the effects of IMLs on glaciers, numerical models must incorporate
198 variable lake levels, a moving ice margin, and the exchange of meltwater between the glacier
199 surface, the lake and the glacier bed. Lake levels fluctuate over time, often by many tens of
200 metres, due to filling and draining (see e.g. Carrivick et al., 2017a; Armstrong and Anderson,
201 2020). Since IMLs in a given area likely sit at varying elevations, one lake may drain into
202 another. Any model framework must therefore account for the location and elevation of each
203 lake, as well as the evolution of individual lake volumes (which can change as the ice margin
204 advances or retreats) and lake water levels. Simulating these dynamic changes is currently
205 technically difficult and requires excessive computing power. Instead, many models use
206 topography and ‘flood-fill’ algorithms to guide the movement and storage of water (Zhu et al.,
207 2006; Berends and van de Wal, 2016). While effective, this approach strongly depends on
208 high-resolution topography and lake bathymetry data.

209 Calving is assumed to be the main effect of a water body on an ice margin, and is therefore
210 an important component of any lake-contact glacier model. To accurately represent calved ice
211 losses, models must consider the relationship between lake water temperature and melting at
212 the ice front, as well as the exchanges of water and heat that cause lake temperatures to
213 fluctuate on daily and seasonal scales. The depth of lake waters relative to ice thickness
214 should be included to allow buoyancy-driven calving, and the destabilising effect of lake
215 drainage effects to be accounted for. Aside from the physical processes, observational data
216 is needed to determine plausible ranges of water depth, water temperature and be topography,
217 and to test the accuracy of model outputs.

218 Numerical modelling of IMLs and their interactions with ice margins around Greenland is a key
219 frontier in glaciology, broached by only a handful of studies (e.g. Carrivick et al., 2020). In turn,
220 interactions between IMLs and ice margins persist with considerable spatio-temporal
221 variability that is not currently accommodated for in numerical models. In the following section,
222 we highlight key research priorities needed to bridge this gap

223

224 **6. Opportunities for further work**

225 IMLs and their influence on ice dynamics in Greenland are an active and growing area of
226 research. Here, we present some directions for further work, with a view to considering IMLs
227 within projections of future mass loss. Perhaps most urgently, multi-temporal inventories of
228 lakes, glacier terminus positions and ice sheet margin extents are needed. Problematically,
229 most techniques for deriving those inventory products rely on satellite images and these
230 present issues of image resolution, image frequency versus clarity (e.g. due to snow cover or

231 darkness during the Arctic winter) and computational power; the spatial coverage needed is
232 extremely large and the spatial resolution required is relatively fine. Furthermore, there is very
233 little data available on lake depths, water temperatures and turbidity. This lake regime data is
234 urgently needed to parameterise numerical models and to answer questions such as ‘does
235 lake temperature vary substantially within a lake, through time, and between lakes?’ or ‘does
236 lake water temperature influence calving rate?’. Overall, the subaqueous (underwater)
237 component of IMLs is virtually unknown, and the extent to which lake waters interact with
238 hydrology beneath glaciers is unstudied. These questions must be resolved in order to
239 determine the exact nature of physical process links between lakes and glaciers; not just
240 during drainage events, which involve abrupt and rapid changes in lake water level, but also
241 ‘normally’, i.e. year-round.

242 A major modelling challenge will be upscaling from a single outlet glacier to larger
243 geographical extents; modelling the entire Greenland Ice Sheet under future climate change
244 scenarios is certainly a big computational task that will require highperformance computing
245 facilities. However, improvements in computer power mean that ever more complex models
246 can be formulated, combined and run over long timescales.

247 Finally, there is always a need for better-quality data, and none more so than ice thickness
248 data. That available for the margins of the Greenland ice sheet is relatively coarse and holds
249 high levels of uncertainty. The location and size of future lakes, as suggested for the
250 Greenland Ice Sheet by Carrivick et al. (2022), have not yet been predicted around the
251 thousands of glaciers and ice caps of Greenland.

252 In the short-term, new technologies and monitoring techniques offer potential advancements,
253 both satellite- and field-based. As well as supporting advanced numerical models, cloud
254 computing has revolutionised the ability to obtain, process and query vast datasets covering
255 huge space and time scales. For example, Landsat imagery since the 1980s can be used to
256 assess landcover changes, including in the extents of ice margins and lakes, at a resolution
257 of 30m (Grimes et al., 2024). Similar image analysis has started to be used to detect lake
258 surface water temperatures (Dye et al., 2021). There are opportunities for multitemporal lake
259 water level datasets from ICESat altimetry products, or from repeat digital elevation models
260 (DEMs). Alternatively, field-based measurements offer observations at higher resolutions than
261 can be achieved with satellite data. For instance, sensors for water depth and temperature
262 can be deployed on semi-autonomous boats, and timelapse camera allow previously
263 unrecognised calving phenomena to be monitored (Mallalieu et al., 2020). Perhaps there is a
264 growing need for a ‘lake data hub’, where IML data can be deposited in a unified and
265 accessible manner for all to use.

266

267 **7. Conclusions**

268 In summary, this article reviews the latest developments in understanding interactions
269 between IMLs and glaciers in Greenland. Given a continued trend of ice margin retreat,
270 Carrivick et al. (2022) suggest that the most likely scenarios appear to be that:

- 271 • Many marine-terminating glaciers will retreat onto land in the coming decades
- 272 • Many land-terminating glaciers will develop lakes, but the persistence of those lakes
273 through time is difficult to assess
- 274 • The effects of IMLs on the ice sheet margin and on glaciers might be most pronounced
275 during the early stages of lake evolution
- 276 • Lakes will impact ice dynamics, but precise physical processes remain challenging to
277 unravel
- 278 • More and larger IMLs probably means more and larger GLOFs

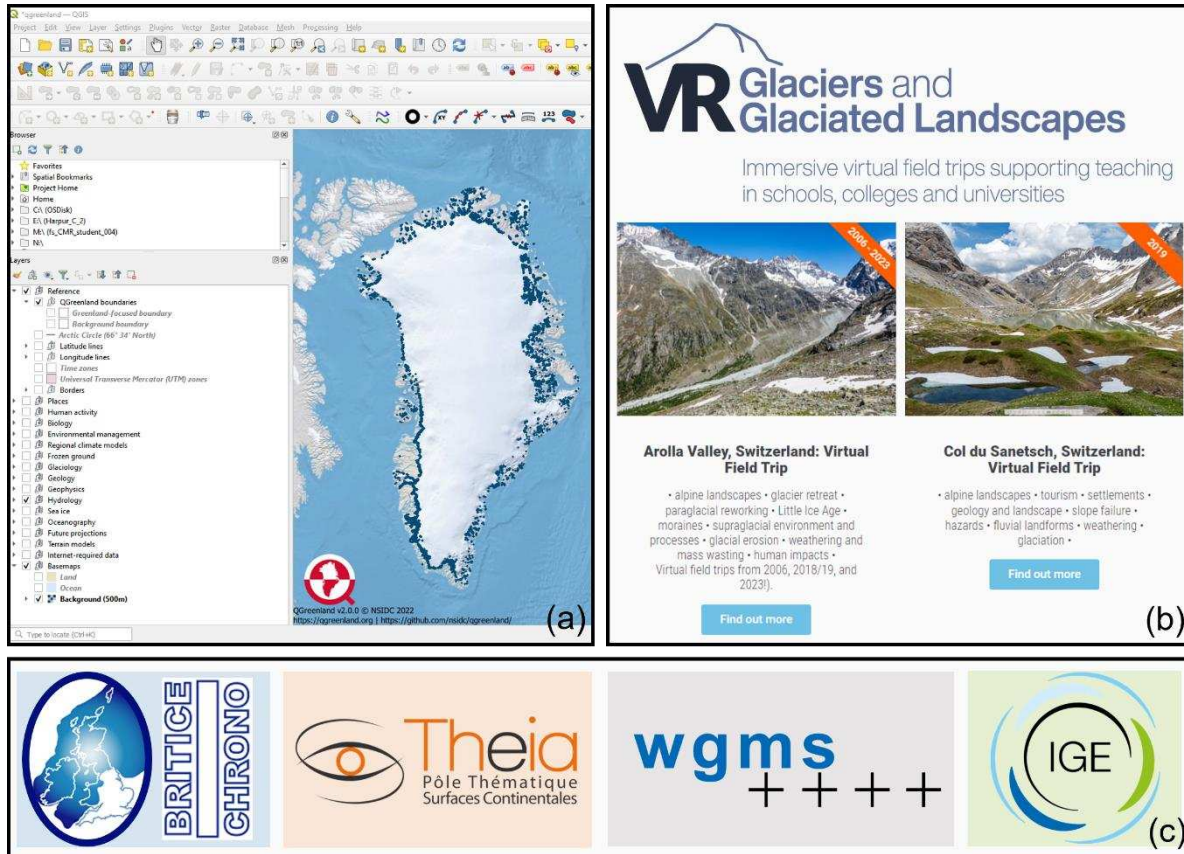
279 Since IMLs are likely to become an increasingly important component of the ice sheet system,
280 understanding their precise impacts on ice loss presents a key frontier within glaciology. Whilst
281 previous studies have gained valuable insights from evidence of IMLs and glacier systems in
282 the past, new observations of physical conditions and processes at IMLs in the present are an
283 essential next step towards their inclusion in ice sheet models. This data, whether produced
284 through in-situ fieldwork or from satellite records, is crucial for improving predictions of the
285 future response of the Greenland's ice sheet, glaciers and ice caps to ongoing climate change.
286 Finally, we recommend this timely and relevant topic as an exciting entry point for students
287 keen to engage with an evolving field of research, and encourage them to explore Greenlandic
288 IMLs further through a wealth of freely accessible resources.

289

290 **8. Educational recommendations**

291 Glacial systems feature as an optional component of all A level geography specifications
292 taught since 2016, with prescribed content ranging from the drivers of ice ages and
293 contemporary distribution of global ice masses to the formation of glacial landscapes and key
294 glacial processes. An expanding range of interactive resources exist to support the teaching
295 and understanding of these subjects, while also allowing students to explore some of the
296 techniques and datasets used within current research. Below and in Figure 5 we highlight
297 several resources that can be used to investigate both Greenlandic IMLs and glacier dynamics
298 more broadly. Many of these employ the use of geographic information systems (GIS) for
299 visualising and analysing glacial data, thereby promoting the development of a key skill for
300 geographers at school, university and in the workplace.

301



302

303 **Figure 5: Resources for student activities, including (A) QGreenland; (B) VR Glaciers**
 304 **and Glaciated Landscapes; and (C) BRITICE-CHRONO, Theia Cartographic Layers, the**
 305 **World Glacier Monitoring Survey and the IGE Worldwide Glaciers Browser.**

306

307 QGreenland (<https://qgreenland.org>) is a free mapping tool for the open-source software QGIS
 308 (qgis.org), which combines a wide range of interdisciplinary datasets into one GIS package
 309 (Moon et al. 2023). Teachers and students can use QGreenland to familiarise themselves with
 310 the wider Greenland environment including its climate, ecology and geology. Of particular
 311 interest to this topic are the 'glaciology' layers (which include ice sheet velocity, thickness and
 312 thinning), the 'satellite imagery' layers, and the 'hydrology' layers, which include an inventory
 313 of approximately 3,300 IMLs mapped from satellite imagery by How et al. (2021). To further
 314 support interpretation and visualisation of changes at land, lake and marine ice-sheet margins
 315 in south-west Greenland from 1992-2015, the ice-margin boundaries and IML outlines from
 316 Mallalieu et al. (2021) can also be downloaded and imported into QGIS from GitHub
 317 (github.com/joemallalieu/gris_margins_and_lakes). Classroom activities using these datasets
 318 could focus on analysing the number and extent of IMLs in Greenland using the Spatial
 319 Statistics tool within QGIS, or on comparing ice velocities or the extent of retreat at lake and
 320 land-terminating margins the within a select region of the ice sheet.

321 For more ambitious students familiar with Google Earth Engine and interested in making their
 322 own maps of ice-margin change in Greenland or beyond, the Google Earth Engine Digitisation
 323 Tool (GEEDiT) (Lea 2018) hosted by the University of Liverpool (liverpoolgee.wordpress.com)
 324 provides this opportunity (we recommend watching the developer's walk-through video
 325 beforehand: youtu.be/UDdR5hRgNTg).

326 There are many free online resources for those interested in exploring IMLs and glacier
 327 dynamics globally . As well as web-based GIS applications and datasets, open-access virtual
 328 reality (VR) resources provide new opportunities to gain immersive experiences of glacial
 329 environments directly from the classroom. Some of the most accessible resources are
 330 described in Table 1.

	Resource	Description	Weblink
Datasets and web apps	Theia Cartographic layers	A GIS compilation of global glacier datasets, including glacier extent (from RGI Consortium 2017), velocity and thickness (from Millan et al. 2019) and elevation change (from Hugonnet et al. 2021).	maps.theia-land.fr
	Université Grenoble Alpes Institute of Environmental Geosciences Worldwide Glaciers browser	Similar to Theia (above), but with 3D visualisation and additional thickness and velocity data for the Greenland and Antarctic ice sheets.	ige-vis.univ-grenoble-alpes.fr
	World Glacier Monitoring Service (WGMS) Fluctuations of Glaciers Browser	A GIS presenting global data on changes in glacier length, area and volume, and associated glacial events including outburst floods.	wgms.ch/data-exploration
	BRITICE	A GIS showing the location of glacial landforms left behind by the ice sheet that covered Britain and Ireland during the most recent glaciation (Clark et al. 2018). Includes geomorphological evidence of IMLs.	briticemap.org
VR and video	VR Glaciers	A number of virtual fieldtrips (covering glaciated landscapes in the UK, Switzerland and USA) to support classroom teaching and geographical skills development for a range of academic levels (McDougall 2019).	vrglaciers.wp.worc.ac.uk
	'Greenland Melting' documentary, PBS	A 12-minute 360° film follows a team of NASA scientists investigating the melting of Greenland's glaciers.	youtu.be/hUWqQ9F3sJk

331 **Table 1: Recommended resources for exploring glaciers and ice sheets worldwide.**

332

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