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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 nvolving 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

introduce Post-16 students to relevant datasets and techniques.

## 1. Introduction

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

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

Studies of glaciers elsewhere – for instance, in Iceland (Baurley et al., 2020), Alaska (Trüssel et al., 2013) and the Himalaya (Zhang et al., 2019) – have shown that glaciers flowing into lakes lose ice much more rapidly than those that terminate on land. IMLs are growing in both number and extent around the Greenland Ice Sheet (How et al., 2021), and this trend is expected to continue through the coming century as the ice sheet progressively retreats (Carrivick et al., 2022). While this landscape change is likely to have significant implications for the stability of the Greenland Ice Sheet, the precise effects of IMLs on Greenlandic glaciers remain poorly understood and are currently missing from models of future ice sheet change. Understanding how lakes alter ice dynamics is crucial for refining projections of ice sheet mass loss, thereby improving our ability to predict future sea level rise. IMLs and glaciers are dynamic indicators of how our world is changing. For students interested in engaging with current climate research, exploring IMLs offers a chance to dive into a rapidly evolving and timely subject with global significance. This topic integrates various strands of the A level/ Higher geography specifications, such as glaciation, geomorphology and spatial data, bridging classroom learning with real-world applications while also highlighting how science tackles the questions presented by climate change.

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

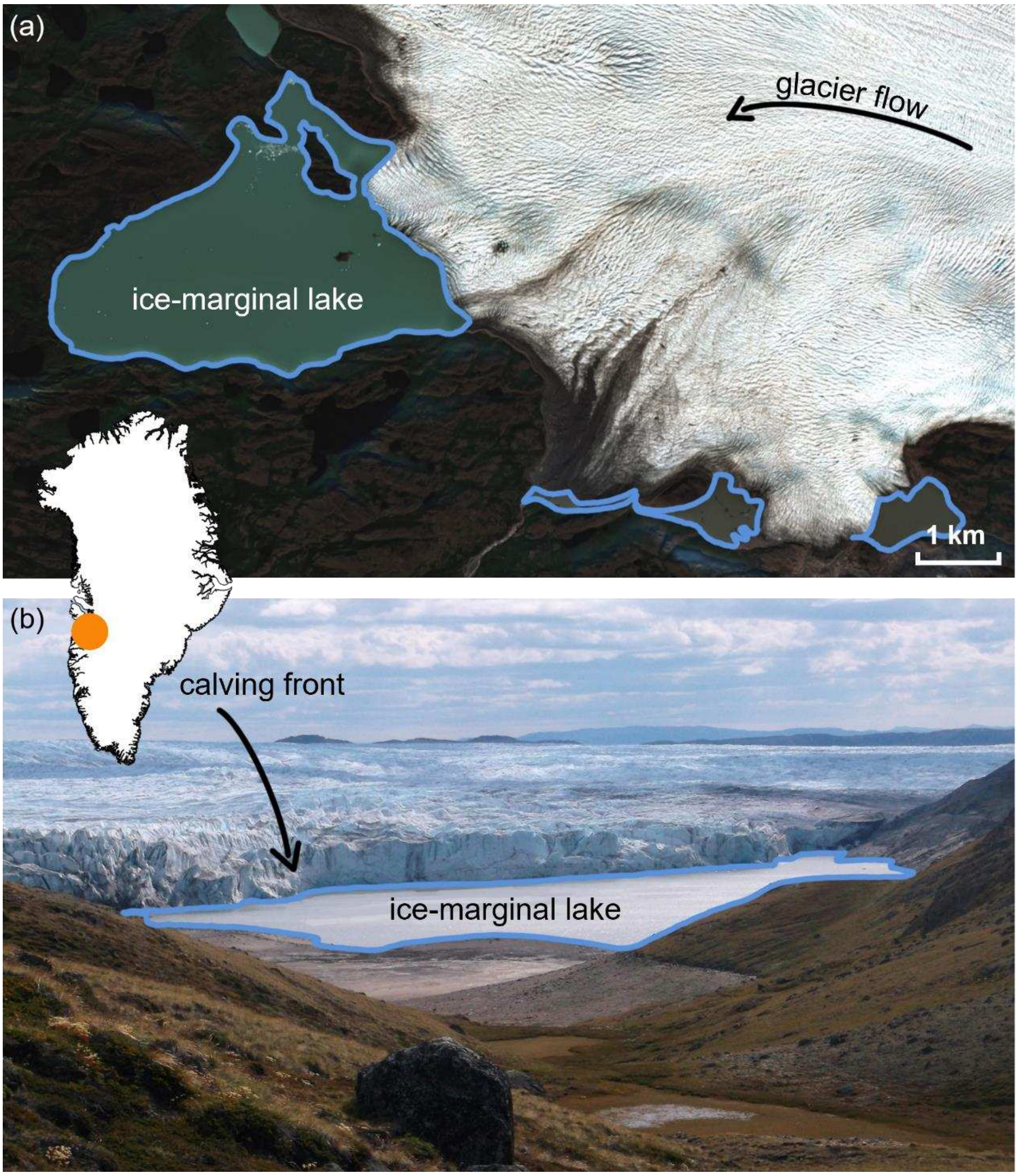

***Figure 1: (a) An ice-marginal lake in west Greenland, visible in Sentinel-2 imagery (courtesy of USGS); (b) An ice-marginal lake on the northern flank of Russell Glacier, west Greenland.***

## 2. Greenlandic ice-marginal lakes in the past

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

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


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

## 3. Ice-marginal lakes in the satellite era

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

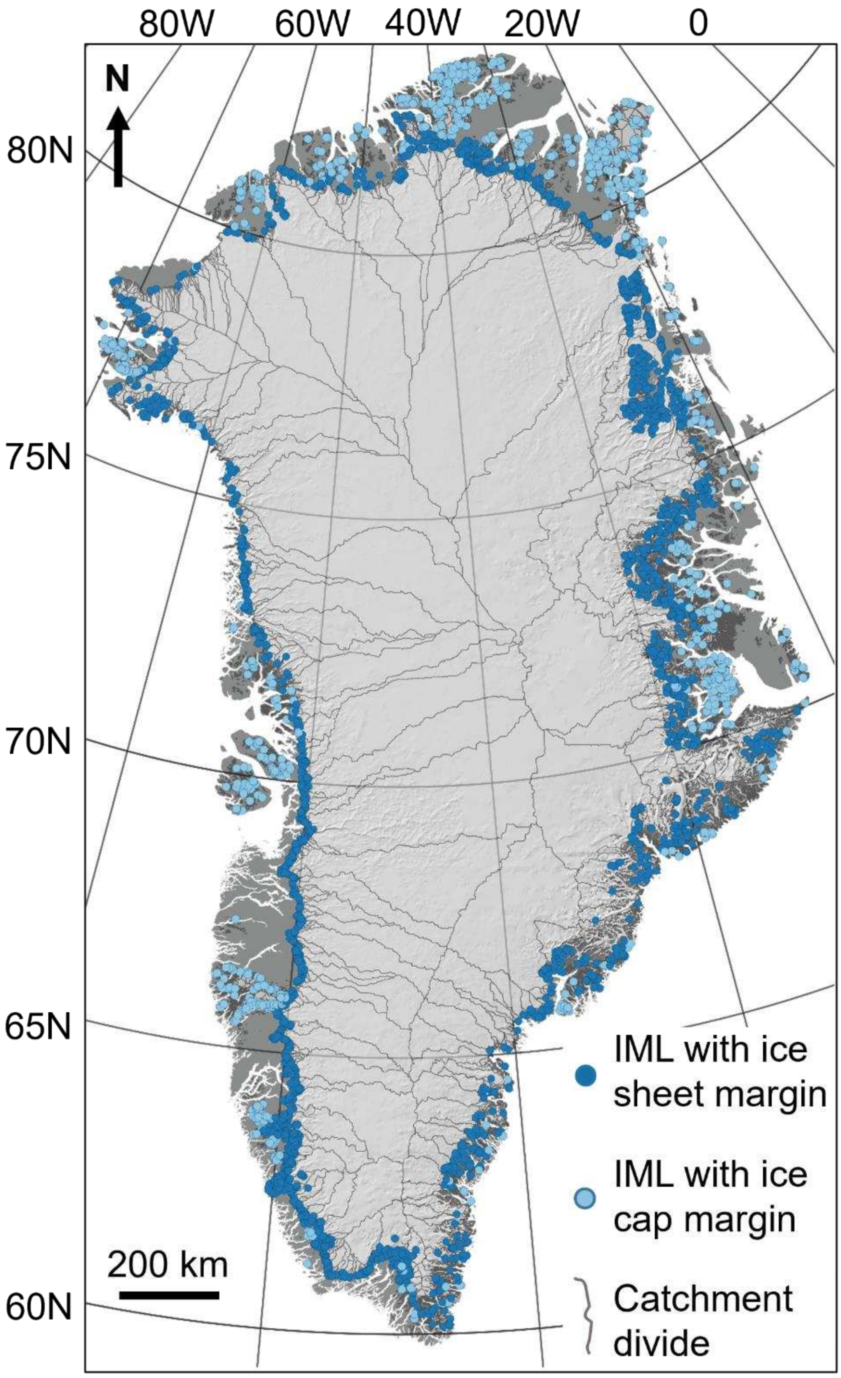


***Figure 3: The distribution of ice-marginal lakes across Greenland, as mapped by How et al. (2021).***

## 4. Ice-marginal lake - glacier interactions

The mass of a glacier or ice sheet is determined by the overall balance between the amount of ice gained and lost. At lake-contact ice margins, the rate of ice mass loss is significantly enhanced by a series of physical interactions between the ice margin and the lake water (Figure 4; Sugiyama et al., 2011; Baurley et al., 2020; Carrivick et al., 2020; Pronk et al., 2021). Foremostly, where glaciers flow into a lake and begin to float, the ice becomes destabilised, fractures and breaks away into icebergs through the process of calving. This is exacerbated when warm lake waters erode notches in the submerged ice front, priming it for failure. Calving rates may also speed up when pressure exerted by the lake on the ice margin decreases. On annual timescales, Greenland's ice margin has been observed to lose stability as ice covering the lake surface melts away at the end of winter and 'unpins' the calving front. Sudden fluctuations in lake water level, such as during a sudden lake drainage event (see e.g. Carrivick et al., 2017a; Dømgaard et al., 2023), can similarly initiate extensive calving (Mallalieu et al., 2020). Over time, if ice mass gains are outpaced by ice mass losses, the ice sheet margin will retreat. Indeed, lake-terminating glaciers in south-west Greenland have been retreating more quickly than their land-terminating neighbours (Mallalieu et al., 2021). This is especially rapid where the underlying topography slopes inland, because recession into progressively deeper water increases the thickness of ice exposed at the lake margin, encouraging more ice loss and resulting in further retreat (see e.g. Sutherland et al., 2020).

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

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

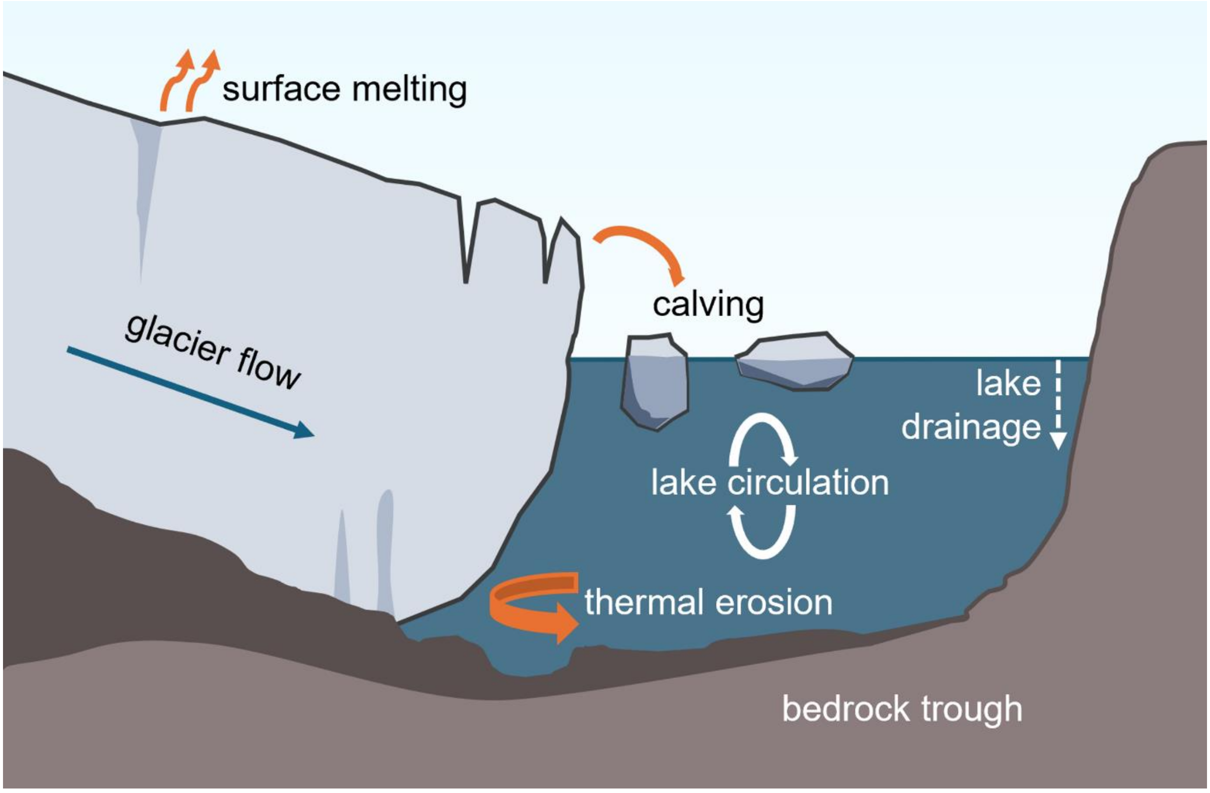


***Figure 4: Key processes within an ice-marginal lake.***

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

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

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

## 6. Opportunities for further work

IMLs and their influence on ice dynamics in Greenland are an active and growing area of research. Here, we present some directions for further work, with a view to considering IMLs within projections of future mass loss. Perhaps most urgently, multi-temporal inventories of lakes, glacier terminus positions and ice sheet margin extents are needed. Problematically, most techniques for deriving those inventory products rely on satellite images and these present issues of image resolution, image frequency versus clarity (e.g. due to snow cover or darkness during the Arctic winter) and computational power; the spatial coverage needed is extremely large and the spatial resolution required is relatively fine. Furthermore, there is very little data available on lake depths, water temperatures and turbidity. This lake regime data is urgently needed to parameterise numerical models and to answer questions such as 'does lake temperature vary substantially within a lake, through time, and between lakes?' or 'does lake water temperature influence calving rate?'. Overall, the subaqueous (underwater) component of IMLs is virtually unknown, and the extent to which lake waters interact with hydrology beneath glaciers is unstudied. These questions must be resolved in order to determine the exact nature of physical process links between lakes and glaciers; not just during drainage events, which involve abrupt and rapid changes in lake water level, but also 'normally', i.e. year-round.

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

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

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

## 7. Conclusions

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

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

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

## 8. Educational recommendations

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

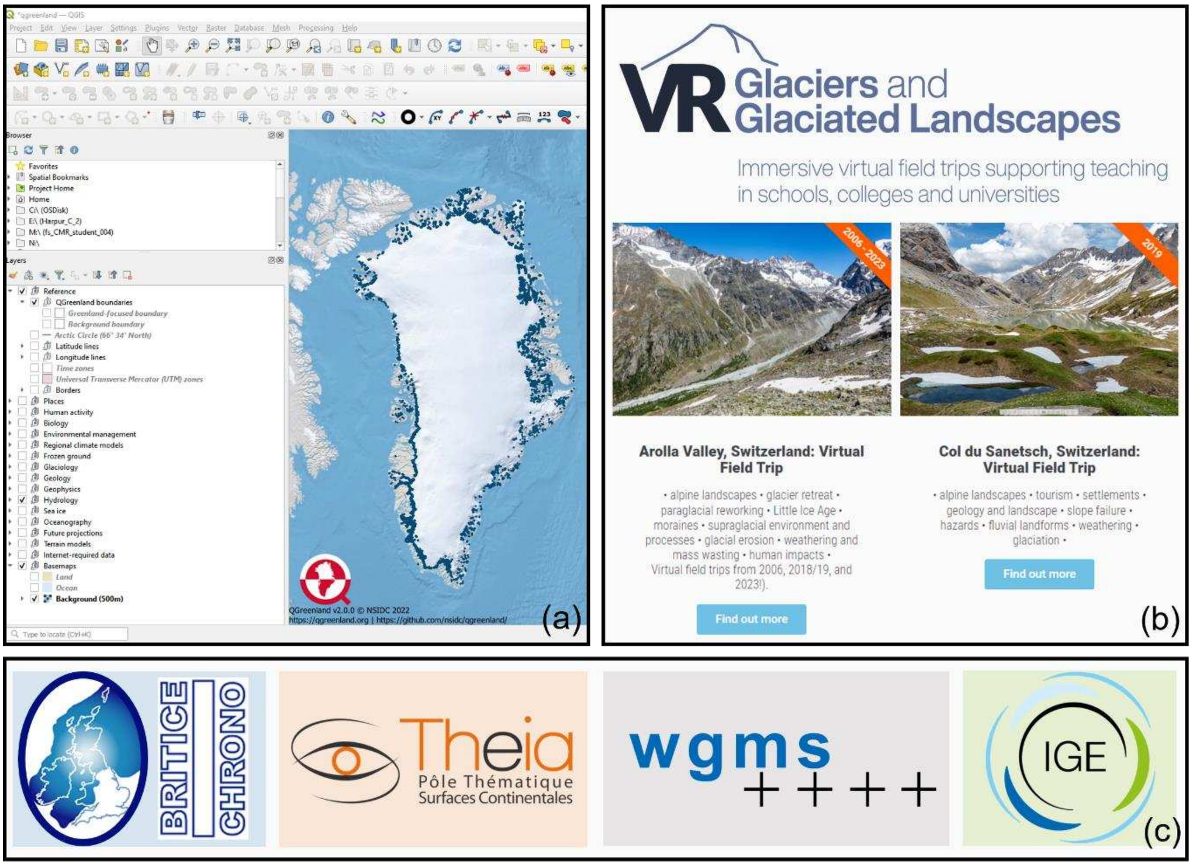


***Figure 5: Resources for student activities, including (A) QGreenland; (B) VR Glaciers and Glaciated Landscapes; and (C) BRITICE-CHRONO, Theia Cartographic Layers, the World Glacier Monitoring Survey and the IGE Worldwide Glaciers Browser.***

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

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

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

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

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