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Ice-Marginal Proglacial Lakes Across Greenland: Present Status and a Possible Future

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Key Points:

- Lakes occupy 10% of the ice margin and vary between 2% and 26% by region
- Ice velocity is ~25% greater into lakes compared to onto land and total ice discharge into lakes is ~4.9 Gt.yr^{-1}
- Thousands of overdeepenings have potential to host more and larger lakes in the future but not all will be ice-marginal simultaneously

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Ice-marginal lakes can affect glacier dynamics but are ignored in studies of the evolution of the Greenland ice sheet (GrIS) and of peripheral mountain glaciers and ice caps (PGICs). Here we show that lakes occupy 10% of the GrIS ice margin and occur on 5% of PGICs. Ice velocity at the GrIS margin is enhanced by ~ 25% at lakes versus on land. Mean ice discharge into lakes is ~4.9 Gt.yr, which is ~1% of ice discharged through marine termini. We locate thousands of subglacial overdeepenings within which 7,404 km^2 of future lakes could form, all of which will be ice-marginal at some time. Future lakes in the west and east will be restricted to the margin of the GrIS and within alpine valleys, respectively. This status and possible future leads us to contend that lakes should be incorporated into projections of Greenland ice loss.

Plain Language Summary Lakes forming on the edges of glaciers can affect ice dynamics but are not included within numerical models of the Greenland ice sheet (GrIS) or of peripheral mountain glaciers and ice caps (PGICs). We show that lakes presently occupy 10% of the GrIS ice margin and occur on 5% of PGICs. We determine that ice is typically moving 25% faster in the vicinity of lakes than at land margins. We estimate that ice discharge into lakes is ~4.9 Gt.yr, which is 1% of that through marine glaciers. We identify thousands of depressions in the landscape that could hold future lakes as glaciers retreat from them. Overall, understanding of lake evolution should be incorporated into projections of Greenland ice loss and runoff.

1. Introduction

The future evolution of the Greenland Ice Sheet (GrIS) is of global concern because its meltwater runoff will contribute tens to hundreds of millimeters of sea level rise through the next century (Goelzer et al., 2020; Hofer et al., 2020; Pattyn et al., 2018; Shepherd et al., 2020; Slater et al., 2020). Especially prominent changes are occurring along the GrIS ice margin as runoff accumulates and the ice margin retreats across complex topography, leading to the formation of more ice-marginal proglacial lakes (Carrivick & Quincey, 2014; How et al., 2021; Shugar et al., 2020). The observed increase in the number and size of lakes is concerning, as transition from land-to lake-terminating ice margins can accelerate ice flow through reductions in longitudinal buttressing force and basal drag near the ice margin due to buoyancy effects (e.g., Carrivick et al., 2020 and references therein). Increases in lake-terminating ice-marginal environments will also increase potential for more rapid ice sheet mass loss through both iceberg calving and lake-enhanced melt of the ice margin itself (e.g., Schomacker, 2010). Ice-marginal lakes have also been invoked as a potential catalyst for inducing exceptionally rapid ice margin retreat (Carrivick et al., 2020; Hinck et al., 2020; Quiquet et al., 2021; Sutherland et al., 2020), especially where there is progressive ice-margin retreat down a retrograde bed slope (Truffer and Motyka, 2016) in a manner highlighted for marine termini by Crawford et al. (2021). These effects of ice-marginal lakes are not directly incorporated into projections of long term GrIS change.

There has been a recent upturn in the attention afforded to ice-marginal lakes as the importance of glacier-lake interactions has become clearer (Carrivick et al., 2020). How et al. (2021) provided a comprehensive and robust inventory of ice-marginal lakes across Greenland and Mallalieu et al. (2021) provided compelling evidence that lakes have a disproportionate impact on ice margin retreat; along a 5,000 km stretch of the western margin of the GrIS margin, retreat between 2010 and 2015 was >4 times greater at lake-terminating margins than that at

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land-terminating margins. However, glacier terminus recession at lake-terminating margins is typically an order of magnitude lower than at marine-terminating glaciers, as shown by comparing Mallalieu et al. (2021: their Table 4) to the hundreds of meters of retreat per year (between 1985 and 2018) reported for hundreds of tidewater glaciers by both King et al., (2020, their Figure 2) and Fahrner et al. (2021).

Though retreat rates of lake margins are less than marine margins, the length of the ice-margin that lakes occupy has not been analyzed, meaning their relative importance is currently unknown. Furthermore, ice discharge into these ice-marginal lake systems is unquantified, especially relative to their marine- and land-terminating counterparts. Perhaps most crucially, the likely evolution of these lakes as the ice margin retreats and thins has not been considered, leaving an open question of how ice-marginal lakes will affect future GrIS recession, mass loss and runoff. Regarding sea level contributions, more lakes and larger lakes could most simply act as bigger water storages if they are endorheic (i.e., have no terrestrial outflow to a river/ocean). However, it is most likely that lakes will fill up to a spillway threshold and then drain freely.

Runoff into the North Atlantic affects ocean circulation and hence the climate of western Europe, which has feedback on human health, behavior and economy (McMichael et al., 2006; Siegert et al., 2020). In Greenland, runoff locally affects the downstream ecosystems, landscape evolution, and the residing population and economy, including hunting, fishing, mining, and hydropower. The aim of this study is therefore to quantify the present status of ice-marginal lakes across Greenland and suggest a possible future state of lakes, ultimately to inform inclusion of ice-marginal lakes with GrIS evolution simulations.

2. Datasets and Methods

The inventory of ice-marginal lakes by How et al. (2021) was taken to be the most contemporary and internally consistent data set available for our analysis and pertains to the year 2017. An ice-margin for the GrIS was derived from the glacier catchments/basins data set of Mouginot and Rignot (2019) and from our own 30 m resolution semi-supervised landcover classification derived from Landsat 8 Operational Land Imager imagery from the summer seasons (July–September) of 2016 to 2019 inclusive. We also herein use the Mouginot and Rignot (2019) basin delineations to aggregate our results by major regions of Greenland (Figure 1). A Greenland coastline for year 2017 was derived from the 150 m resolution land mask BedMachine (v3) datasets and updated for glacier front positions in 2017 by Gerrish (2020).

In this study, these ice sheet and ice-marginal lakes datasets were intersected and the ice sheet and the coastline were intersected to delineate our lake boundaries and marine termini, respectively (Figure SI_1 in Supporting Information S1). We computed the number and length of glacier-lake boundaries for the GrIS and for the peripheral mountain glaciers and ice caps (PGICs), the total area of lakes adjoining glaciers, the ice discharge (as a function of the velocity and ice thickness) through each lake boundary and the drainage basin/catchment area for each lake. PGICs were those in Randolph Glacier Inventory v6 obtained from GLIMS (2021) (Raup et al., 2007). Boundaries were represented as points with 200 m spacing to ensure consistency with the resolution of the ice margin of Mouginot and Rignot (2019), which we relied on for our length calculations, and to match the resolution of the velocity grids of Joughin (2020). Ice discharge was calculated as the product of the ice thickness from BedMachine v4 (Morlighem et al., 2021) and ice velocity, for which we computed the mean of five ice sheet wide 200 m resolution annual datasets from December 2014 to November 2019 by Joughin (2020). The drainage basin/catchment for each lake was determined using hydrological analysis of the ice surface data set of BedMachine v4. Catchments were estimated via computation of a flow direction grid that was derived from a digital elevation model (DEM) from BedMachine v4 (Morlighem et al., 2021), smoothed using a moving window of 10 cells, and then filled local depressions. More details of all the datasets we used and generated and our methods are in Supporting Information S1.

We also considered possible locations and size of lakes in the future by analyzing topographic basins, or subglacial overdeepenings, that will become revealed and available to hold meltwater as the GrIS margin retreats inland. We generated a future GrIS outline by subtracting the mean ice thickness change as suggested by multiple models at 5 km resolution in the ensemble study of ISMIP6 (Goelzer et al., 2020; see their Figure 6a) from the BedMachine v4 ice thickness. We determined overdeepenings by filling local depressions in the BedMachine v4 (Morlighem et al., 2021) bed topography data set. Overdeepenings were filtered for >0.1 km^2 to be mindful of the resolution of the datasets and uncertainty within them (see our Supporting Information S1). Those

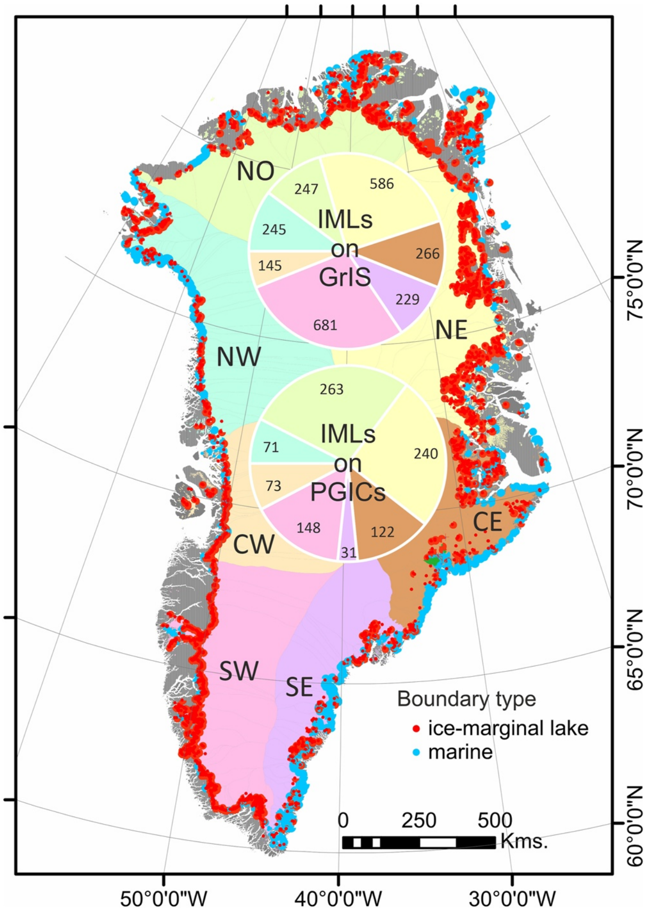

Figure 1. Overview of location and number of ice-marginal proglacial lakes (IMLs) and marine termini discriminated per region both on the edge of the Greenland Ice Sheet (GrIS) and on peripheral ice caps and glaciers (PGICs). Regions are those by Mouginot and Rignot (2019), where NO denotes North, NE north east, CE central east, SE south east, SW south west, CW central west and NW north west.

overdeepenings intersecting the coastline and below sea level were interpreted as fjord troughs and excluded from our reported statistics of possible future lakes (Figure 4). We are unable to consider the rate of lake growth or whether lakes might drain, for example,

3. Results

How et al. (2021) identified 2,399 ice-marginal lakes >0.05 km^2 on the GrIS and 948 on PGICs, with a total area of 3,214 and 761 km^2, respectively. This study finds a total lake-glacier boundary length of 3,176 km (Table SI_1 in Supporting Information S1), which means that on average 10% of the GrIS has an ice-marginal lake boundary, and there is one lake every 13 km length of the GrIS ice margin. For PGICs, ~5% of those margins terminate in an ice-marginal lake. Ice-marginal lake environments therefore substantially exceed those of marine termini, which total 1,698 km or 5% of the GrIS margin length, and they total 615 km on PGICs (Table SI_1 in Supporting Information S1). Marine termini occupy 486 km, or 12% of the regional ice margin length in the north-west (NW) region, 8% in central-west (CW) and 6% in north (NO) and south-east (SE) (Table SI_1 in Supporting Information S1).

In the NO region 15% of PGICs have lakes. Four regions stand out for containing the greatest number and total size of ice-marginal lakes; namely NO PGICs with 28% of the total PGICs lake number and 17% of the total PGICs area, NE GrIS with 24% of the total GrIS lakes number and 35% of the total GrIS area, NE PGICs with 25% of the total PGICs number and 38% of the total PGICs area, and south west (SW) GrIS with 28% of the total GrIS number and 29% of the total area of ice-marginal lakes on the GrIS (Figure 1; Table SI_1 in Supporting Information S1).

The total length of glacier – lake boundaries is 3,176 km on the GrIS, which is 10% of the total GrIS ice margin, and 795 km on PGICs. The greatest proportions of the GrIS with lake boundaries occur in the NE (26% of the region ice margin length), SW (17%), CW (16%) and NO (11%) (Table SI_1 in Supporting Information S1). Glacier – lake boundary lengths do not vary greatly between regions and have a median length of ~0.5 km long on both the GrIS and on PGICs (Figure 2a). They are unusually long and >1 km in the SE PGICs (Figure 2a). In contrast, the length of marine termini do vary greatly between regions, and tend to be longer on the GrIS than on PGICs and are greatest (median >3 km) in the NW, NO, NE and CW regions (Figure 2a).

Ice velocity at lake boundaries is greater than at land boundaries for all regions of the GrIS (Figure 2b). With all regions combined the lower quartile, median, and upper quartile of ice velocity for lake boundaries is 25%, 25% and 30% greater than for on land, respectively. The lakes - land difference (both absolutely and proportionally) is most pronounced in the CE and CW regions (Figure 2b). In comparison, our marine boundaries have a median velocity of 158 m.yr^{-1} (the skewed distribution has a mean of 678 m.yr^{-1}) and so with the flux gate analysis of tidewater glaciers by Mouginot et al. (2019), which shows typical ice velocities of hundreds to thousands of meters per year, it can be inferred that ice velocities into lakes, whilst enhanced relative to land-terminating margins, are one to two orders of magnitude lower than at marine boundaries.

The total drainage basin area/catchment size of ice-marginal lakes across Greenland has an upper limit of between 408,880 and 497,600 km^2, or 24%–29% of the total GrIS area (Figure 3a). Given that we used hydrological analysis on a smoothed 150 m DEM and Mankoff, Noël, et al. (2019) used different hydrological tools on a 100 m DEM it is encouraging to see broad agreement in our lake catchment estimates and their land catchments (Figure 3a); they did not discriminate lakes. It is perhaps useful to note that the hydrological outlets and basins datasets of Mankoff, Noël et al. (2019, see their Figure 1) suggest a total drainage basin/catchment area of land-terminating

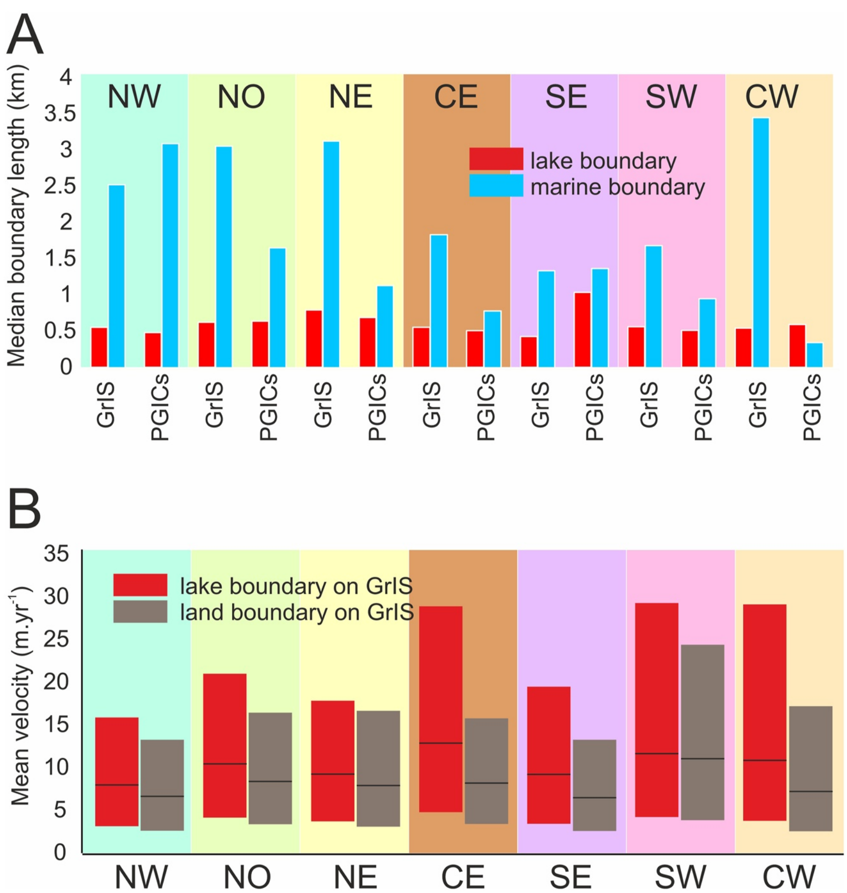

Figure 2. Comparison of boundary length (a) and mean velocity with boundary type (b) discriminated by region both for the Greenland ice sheet (GrIS) and for PGICs. Inter-quartile range and maximum lake sizes are not displayed for clarity in panel (a) The inter-quartile range and median are represented in panel b by a bar and a horizontal line, respectively.

(including lakes) parts of the GrIS to be 589,700 km^2, or 34% (Figure 3a). Our lower estimate is without any leniency for error in the boundary positions and mindful of the 200 m velocity grid resolution, whilst the higher estimate is more lenient by allowing a 500 m tolerance in boundary position and in ice drainage routing (which is in part derived from the velocity grid). The reason for suggesting that this estimate of drainage basin/catchment areas to ice-marginal lakes is an upper limit is because low-order drainage lines (in the vicinity of lakes) link to higher-order lines (in outlet glaciers) and knowing where to limit the extent of the analysis is a very subjective decision. Nonetheless, some ice-marginal lakes have drainage basins/catchments that might stretch into the interior of the GrIS (Figure 3); although if so, they considerably overlap marine-termini catchments. Some overlap is possible between lake and marine catchments with our method because not all ice-marginal lakes are at glacier termini; some are on flanks of outlet glaciers. The median size of an ice-marginal lake drainage basin, using our most conservative or least lenient method, is 159 km^2 (Figure 3b), but there is a large inter-quartile range of 26–839 km^2. For comparison and as will be discussed later, Mouginot (2019) states that ~ 86% of the GrIS drains through marine termini.

We estimate that ice discharge through ice-marginal lake boundaries totals 4.9 Gt.yr^{-1} and that the SW region contributes 37% of this total (Table SI_2 in Supporting Information S1). A large (~30 km^2) lake at Uukkaasorsuaq, which lies in the SW region of Greenland and ~45 km east from the settlement of Paamiut stands out for receiving a relatively very large discharge of ice estimated at 0.74 Gt yr^{-1}. Tininnilik in the CW region receives ~0.18 Gt yr^{-1}. There are five lakes in total estimated to receive >0.1 Gt yr^{-1} and 84 lakes receiving >0.01 Gt yr^{-1}. For our marine boundaries, we calculate a total of 426 Gt yr^{-1} ice discharge, which is in good agreement with the 488 ± 49 Gt yr^{-1} reported for tidewater glaciers by Mankoff, Colgan, et al. (2019) but less than the 555 Gt yr^{-1} reported by Mouginot et al. (2019) for the year 2018 (and mean 535 Gt yr^{-1} for 2009–2018). Our

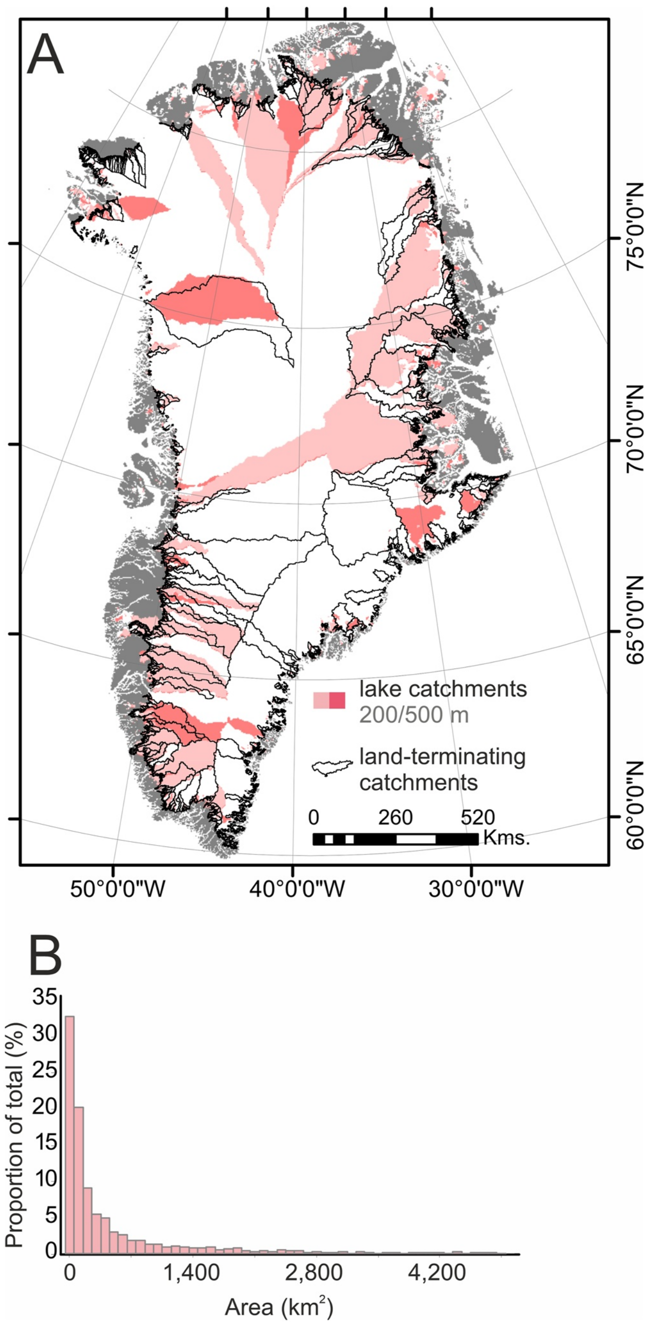

Figure 3. Catchment areas of ice-marginal lakes (a), where darker shades denote usage of a more lenient parameterization and each is in addition to the area estimated with the lower leniency. Land-terminating catchments in panel a are from Mankoff, Noël et al. (2019). Histogram analysis of the areal extent of the catchment areas highlights predominance of smaller lake catchments (b).

ice discharge through marine boundaries is in good agreement in pattern between regions with those of Mouginot et al. (2019; see our Table SI_3 in Supporting Information S1). Therefore, our conservative estimate of the ice flux into ice-marginal lake margins is ~1% of the marine total but given the ice thickness uncertainty (see our Supporting Information S1) could be up to 3.2%.

In the future, up to the year 2100, proglacial lakes could form within 6,247 topographic basins/overdeepenings >0.1 km^2 (Figure 4). Overdeepenings below sea level are not included in our statistics because once ice disappears from and exposes those troughs, they will become flooded by seawater as fjords (Figure 4). Assuming all these overdeepenings are simultaneously full, which is very unlikely as the ice margin will retreat progressively inland, then future lakes could total 7,404 km^2(Figure 4). The greatest changes in distribution of lakes between the present (Table SI_1 in Supporting Information S1) and those possible in the future (Table SI_3 in Supporting Information S1) could be in the CE region (+14% of the GrIS total) and the SW (−14%). The greatest changes in the total size/coverage of lakes per region could be in the CE (+18%) and in the NE, NO and SW regions (−15%, −10% and −24%, respectively). This spatial variability in possible lake formation is because the ice sheet margin in the west is not projected to retreat inland greatly (Figure 4), despite a lot of the ice being on a retrograde slope. In contrast, future lakes in the east could form abundantly within numerous deglaciated deep valleys (Figure 4). Some future lakes could be extremely large; 59 lakes >20, 14 lakes >50 and 3 lakes >100 km^2, with the largest being 161 km^2. Notwithstanding the fact that not all these lakes will co-exist, the median size of possible future lakes is 0.24 km^2, which is 50% greater than at present, and the inter-quartile range increases from 0.15 at present to 0.57 km^2.

4. Discussion

Ice-marginal lakes are ubiquitous and pervasive in all parts of Greenland, both on the GrIS and across Greenland PGICs (Figure 1) but studies of their evolution and ice-interactions tend to be on individual lakes only (e.g., Carrivick & Tweed, 2019; Carrivick et al., 2017; Grinsted et al., 2017; Kjeldsen et al., 2017; Mallalieu et al., 2017, 2020; Weidick and Citterio, 2011; and references therein). As the quality and quantity of remotely-sensed imagery increases and as computing power expands, there is increasing ability to not only inventory these lakes (c.f. How et al., 2021) but also to capture their dynamics; for example, many lakes in Greenland often fill, drain, coalesce or become detached from ice margins (Carrivick & Quincey, 2014; Carrivick & Tweed, 2019).

The boundary between a glacier and a lake is the interface through which mass and energy interactions occur; most profoundly by water exchanges (e.g., runoff supraglacially and subglacially), sediment deposition, mechanical forces (e.g., longitudinal stress, buoyancy) and thermal energy fluxes (e.g., direct melt of the ice margin and impacts on the proglacial water body) (Carrivick & Tweed, 2013; Carrivick et al., 2020; Truffer and Motyka, 2016). Therefore, the length of that boundary is a key parameter to determine to quantify any effects of that lake on glacier morphology and behavior. Other key properties are lake depth and lake water temperature (Carrivick et al., 2020), but these are rather more difficult to derive from remote sensing and field data on both is extremely sparse. Notably, some progress on determining ice-marginal lake surface temperatures has recently been made (Dye et al., 2021) but remotely-sensed surface temperatures are limited, as they do not effectively represent water temperature at depth, or temperature through the water column and associated

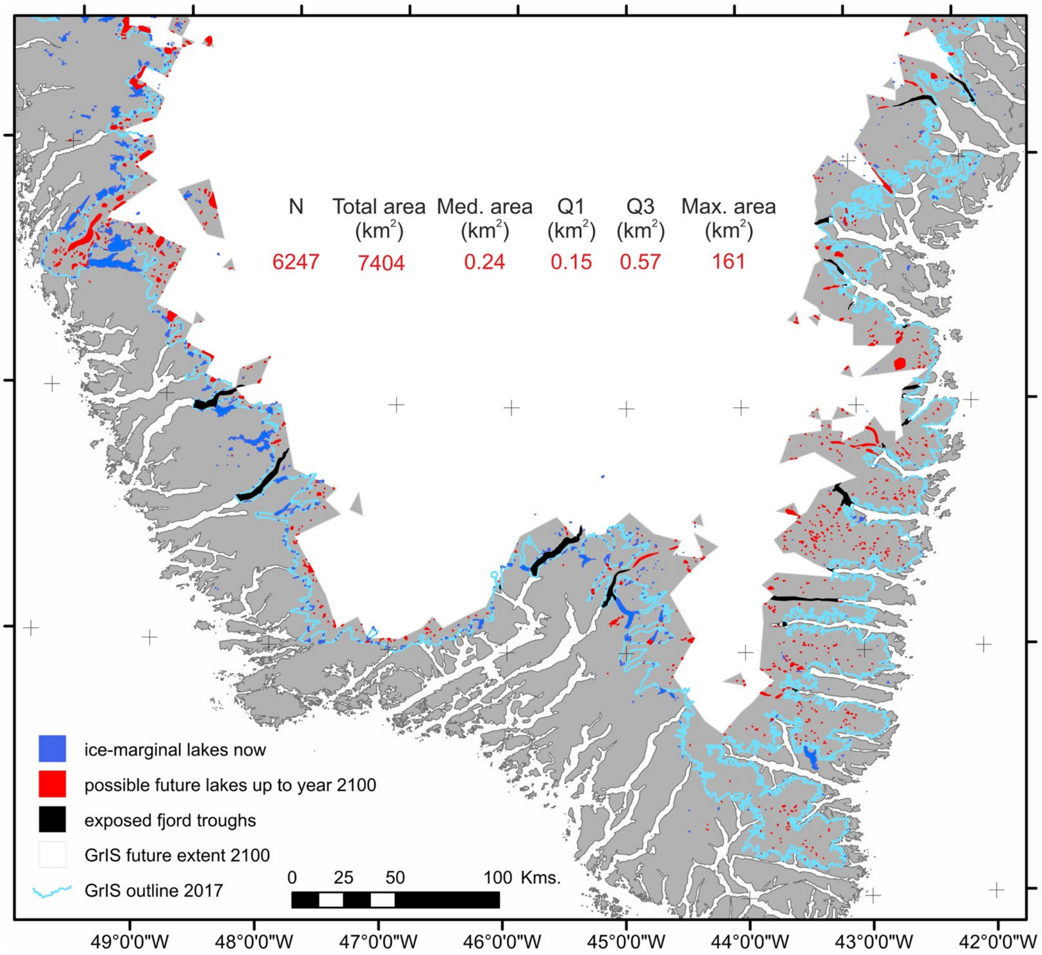

Figure 4. Location, number and size of overdeepenings, within which lakes could form in the future. Future 2,100 ice extent is the mean of several models at 5 km resolution evaluated and reported by Goelzer et al. (2020). Inset statistics are for the whole of the Greenland ice sheet (GrIS), not just the southern part, which is depicted here to highlight the spatial differences. Note that the possible future lakes are a maximum estimate because not all will be ice-marginal simultaneously; many will become detached from the ice margin, and because we cannot suggest if all overdeepenings will completely fill with meltwater and not drain.

seasonality (c.f. Sugiyama et al., 2021). The length (and thickness) of a glacier – lake boundary is important for controlling lake evolution. Specifically, it has been correlated with the rate of ice-margin change (and therefore lake evolution) in west Greenland (Mallalieu et al., 2021) and the Gulf of Alaska (Field et al., 2021). Given that we have established that 10% of the GrIS is presently in contact with a lake, and that individual glacier-lake boundaries can be many kilometres long (Figure 2), then greater attention needs to be given to these environments if the future evolution of the GrIS is to be better understood. How GrIS and PGIC ice discharge will evolve in response to the formation of (more and larger) ice-marginal lakes is unknown but will be dependent on location-specific topographic settings.

Comparing our catchments for lakes and those for land and marine-termini (Mouginot, 2019; Mankoff, Noël et al., 2019) shows some agreement (Figure 3a), some dependence on datasets and methods, but also considerable uncertainty in the accuracy of results. Catchments delineated using analysis of ice dynamics (c.f. Mouginot and Rignot, 2019) are too coarse for ice-marginal lake analysis owing in part to the method but also because catchments for many parts of the land-terminating sectors of the ice sheet being aggregated by those authors. There is a clear need for refining the catchments of ice-marginal lakes to understand the inland/up-ice extent of glacier-lake boundary influences/effects. Price et al. (2008) have modeled ice-marginal perturbations propagating tens of kilometres inland or up-ice, which accords with longitudinal coupling being effective up-stream between four and 10 times ice thickness (Cuffey & Paterson, 2010). The spatial scale of these effects for glaciers with ice-marginal lakes needs resolving because they are likely to be smaller and slower than that considered by Price et al. (2008). The presence/absence of a lake, water level, water temperature and any sudden changes in those lake properties could affect glacier dynamics within lake catchments. Importantly, the alpine literature (e.g., see citations within Carrivick et al., 2020) and numerical models (Hinck et al., 2020; Quiquet et al., 2021; Sutherland et al., 2020) show that these effects could persist many kilometres up-ice from those lakes, especially where glaciers sit on retrograde bed slopes (i.e., overdeepened valleys/basins).

Ice velocities on the edge of the GrIS are locally enhanced by ice-marginal lakes compared to those from land terminating margins (Figure 2b, Figure SI_1b in Supporting Information S1) typically by a factor of ~+25%. The association of faster-flowing ice with ice-marginal lakes compared to glaciers terminating on land is relatively well-documented elsewhere (e.g., Baurley et al., 2020; Dell et al., 2019; King et al., 2018; Liu et al., 2020; Pronk et al., 2021; Sato et al., 2021; Sutherland et al., 2020; Tsutaki et al., 2013, 2019, 2011). However, for the GrIS, whilst ice velocities might be higher in the vicinity of lakes than at land-terminating ice-margins (Figure 2b, Figure SI_1b in Supporting Information S1), this does not currently translate into receipt of very much ice (discharge) because; (a) whilst acknowledging the large uncertainty in the ice thickness data set especially on the margins of the GrIS the ice in those areas is thin, at least in comparison to the thickness of marine terminating outlet glaciers (Figure SI_1b and 1d in Supporting Information S1) and, (b) at present ice-marginal lakes on the GrIS are predominantly situated on the lateral margins of glaciers, that is, oblique to the main flow direction, rather than at termini (e.g., Figure SI_1a in Supporting Information S1).

Future lakes in west Greenland will probably remain restricted to the ice margin, which is not projected to change much in its position compared to the east (Figure 4). In contrast, in east Greenland the projected future deglaciation of deeply incised valleys reveals a landscape conducive to retaining lakes that are both numerous and large (Figure 4), and these topographic settings will be conducive to a much higher proportion of those lakes (than at present) forming at glacier termini where they can have a much more profound impact on ice dynamics. Thus, the future of east Greenland in terms of ice-marginal lakes developing on glacier termini will become rather more like the situation for PGICs at present. Furthermore, our analysis shows how some marine-terminating outlet glaciers (in all regions of Greenland) will lose contact with the ocean/coastline and their termini will retreat inland to become land-terminating (Figure 4), as has already been happening over the last decades (Kochtitzky & Copland, 2022). Notwithstanding that lake effects on glaciers predominantly operate on time-scales of decades (Carrivick et al., 2020; Sutherland et al., 2020), which can be an order of magnitude less than effects of marine boundaries on ice sheets, these conditions of more and larger lakes (Figure 4) lead us to suggest that the relative importance of lakes on the GrIS could increase in the future.

5. Conclusions

Lake-terminating ice margins are approximately twice as extensive on the GrIS as their marine counterparts. Yet relatively little is known about them and how they might evolve in the future. Ice velocity into lakes is typically 25% greater than for glaciers that terminate onto land. The difference in velocity between lake- and land-terminating parts of the ice margin is most pronounced in the CE and CW regions. As much as 24% to 34% of the GrIS area could now deliver ice into ice-marginal lakes, but these lake catchments overlap those of marine termini and they have a large uncertainty dependent on datasets and methods used. Ice discharge into ice-marginal lakes around the GrIS is estimated to be 4.9 Gt.yr, which is just 1% of that through marine termini at present. However, as many marine termini can be expected to become land-terminating in the future and as proglacial landscapes expand revealing overdeepenings into which meltwater will pond to form lakes, the relative importance of ice-marginal lakes on GrIS evolution can only be expected to increase. Resolving the importance of glacier – lake interactions for the future evolution of the GrIS requires intensive and extensive field data, spatio-temporal lake inventories, much better delineation of lake catchments, and incorporation of lake-glacier interactions as mechanistic processes and feedbacks into ice sheet models.

Data Availability Statement

Ice-marginal lakes are available from How et al. (2021). https://catalogue.ceda.ac.uk/uuid/7ea7540135f441369716ef867d217519. Greenland ice sheet catchments are available from Mouginot and Rignot (2019) http://doi.org/10.7280/D1WT11. Hydrological catchments of the GrIS are available from Mankoff, Noël et al. (2019)

https://dataverse01.geus.dk/dataverse/freshwater. A Greenland coastline is available from Gerrish (2020) http://doi.org/10.5285/8CECDE06-8474-4B58-A9CB-B820FA4C9429. PGICs are available from RGI v6 obtained from GLIMS (2021; Raup et al., 2007) http://glims.colorado.edu/glacierdata/. Annual ice velocity grids are available from Joughin (2020) https://nsidc.org/data/nsidc-0725/versions/2. Ice surface elevation, ice thickness, ice sheet bed topography from BedMachine v4 (Morlighem et al., 2021) http://doi.org/10.5067/VLJ5YXKCNGXO. Our shapefiles of lake and marine boundaries (lines), ice discharge into lakes (points), lake catchments (polygons) and overdeepenings/possible future lakes (polygons) are available via the Research Data Leeds Repository http://doi.org/10.5518/1107.

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