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Greenland's ice-marginal lakes represent an important and dynamic component of meltwater storage

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Abstract. Ice-marginal lakes are important components of glacierised landscapes, storing meltwater, influencing glacier dynamics, and regulating freshwater transfer to the ocean. Greenland (Kalaallit Nunaat) hosts a large concentration of ice-marginal lakes along the edge of the Greenland Ice Sheet, and its peripheral glaciers and ice caps. Here, we present a Greenland-wide remote sensing assessment of ice-marginal lakes between 2016 and 2025 to provide a comprehensive overview, and evaluate their role with ongoing glacier change. We identify 4038 lakes covering 4734.9 km^2, equivalent to 1 % of Greenland's ice-free land area. Lake number, area, and surface temperature show negligible change over the decade, indicating broadly stable conditions. However, in total these ice-marginal lakes store an estimated 462.5 Gt of meltwater, of which 67.0 Gt (14 %) has the potential to be rapidly released through glacial lake outburst floods (GLOFs). Our results demonstrate that ice-marginal lakes are a major and spatially heterogeneous component of Greenland's meltwater system, functioning both as long-term water storages and as sources of episodic, high-magnitude outflow events. Their role remains under-represented in assessments of Greenland hydrology and freshwater fluxes, with implications for constraining Greenland's contribution to global sea-level estimates.

1 Introduction

Ice-marginal lakes form at the terrestrial margins of ice sheets, ice caps and glaciers, acting as reservoirs of meltwater that modulate the timing and magnitude of freshwater delivery to downstream environments and, ultimately, the ocean (Compagno et al., 2022; Harpur et al., 2025; Rick et al., 2023; Shugar et al., 2020; Veh et al., 2023). Ice-marginal lakes can be exceptionally dynamic, periodically releasing stored meltwater through sudden and quick drainage events caused by failure of moraine dams or ice flexure and fracture (Carrivick and Tweed, 2019; Veh et al., 2026). The resulting glacial lake outburst floods (GLOFs), also referred to as jökulhlaups (Icelandic) or sermimit supinerit (Kalaallisut, New Greenlandic), cause rapid re-configuration of subglacial hydrology, with consequences for ice dynamics and proglacial geomorphology, ecosystems and fjords (e.g. Weidick

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and Citterio, 2011; Grimes et al., 2024). GLOFs also pose significant hazards to downstream communities, infrastructure, and livelihoods in cases where populations reside in downstream landscapes, such as the Himalaya (Zhang et al., 2024a).

On a global scale, ice-marginal lakes are typically considered within the broader category of "glacial lakes". Remote sensing studies consistently suggest that glacial lakes have increased in both number and area over the past decades, reflecting enhanced meltwater production and widespread glacier retreat (Shugar et al., 2020; Zhang et al., 2024b, a; Ke et al., 2024; Song et al., 2025). Despite this overall growth, the global glacial lake distribution is highly skewed with the 40 largest lakes storing approximately half of total global glacial lake volume, whereas small lakes (0.01–0.1 km^2) account for 77 % of lake numbers but only 12 % of total volume (Song et al., 2025; Veh et al., 2026). Additionally, the frequency and characteristics of GLOFs are evolving. Many ice-marginal lakes dammed by ice can drain when the lake becomes deep enough to exceed ice overburden pressure, causing the ice dam to float. As the ice dam thins, the threshold for floatation is reached at progressively lower water levels, reducing the volume that these lakes can store before draining (Lützow et al., 2023; Veh et al., 2023, 2025).

Greenland (Kalaallit Nunaat) hosts approximately one third (34 %) of the world's ice-marginal lakes (i.e. ice-contact) at the margin of the Greenland Ice Sheet, and the margins of Greenland's peripheral glaciers and ice caps (PGICs) (Song et al., 2025; Veh et al., 2026). However, global-scale classifications of glacial lakes are subject to key limitations when applied to Greenland; largely due to the extensive latitudinal range that presents varying lake conditions which are challenging to classify with a single classification method (How et al., 2025b). For example, persistent ice cover obscures lake boundaries and necessitates indirect classification approaches (Wangchuk and Bolch, 2020; How et al., 2021). As a result, global inventories may omit or mis-classify glacial lakes, limiting their utility for understanding regional-scale processes.

Existing Greenland-wide assessments indicate that there were 3347 ice-marginal lakes in 2017, occupying approximately 1-10 % of the ice sheet margin and 5 % of the margins of PGICs (Carrivick et al., 2022; How et al., 2021; Ryan et al., 2024). In total, 326 of these lakes have been identified as GLOF-producing lakes with 541 drainage events documented between 2008 and 2022 and elevated activity coinciding with extreme runoff years (Dømgaard et al., 2024a). Change analyses suggest that both lake number and total area increased from the 1980s, followed by relatively small fluctuations over the past decade (Carrivick and Quincey, 2014; How et al., 2021). In addition, small lakes (< 0.1 km^2) have exhibited warming trends up to 0.2 °C on average from 2016 to 2023, similar to observations in Arctic Sweden and Patagonia (Dye et al., 2021, 2025; How et al., 2025b; Zhao et al., 2025). Looking to the future, continued ice retreat is expected to expose subglacial over-deepenings and form new lakes with a projected total area of up to 7,404 km^2 by 2100 (Carrivick et al., 2022). In addition, existing lakes may decrease in size or vanish all together due to ice thinning and retreat, underlining the complexity of projecting future occurrences of ice-marginal lakes (Harpur et al., 2026)

A key limitation in understanding the significance of ice-marginal lakes is the absence of robust, spatially comprehensive estimates of lake volume. While global glacial lake inventories provide first-order approximations, these are derived from empirical scaling relationships that are subject to uncertainties arising from incomplete glacier delineations, simplified lake geometries and a lack of in situ validation (Qi et al., 2022; Veh et al., 2026; Zhang et al., 2023). Consequently, ice-marginal lakes and their evolution throught time represent an important, yet poorly constrained, component of the cryosphere and proglacial systems in Greenland. At present, the change in meltwater storage at the terrestrial margin is largely disregarded in

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model projections of glacier dynamics and future sea level contribution from the Greenland Ice Sheet (e.g. Aschwanden et al., 2019; Goelzer et al., 2020; Shafeeque et al., 2026). This represents a critical knowledge gap, as volumes estimates are urgently needed to quantify meltwater storage and release to global sea level.

Here, we present a Greenland-wide assessment of ice-marginal lakes from 2016 to 2025 using satellite remote sensing. We compile annual records of lake number, surface area, surface temperature and glacial lake outburst flood occurrence, together with estimates of lake volume, to quantify changes in terrestrial meltwater storage and assess the role of ice-marginal lakes within the evolving cryosphere of the Greenland Ice Sheet and PGICs.

2 Methods

2.1 Ice-marginal lake classification

The dataset associated with the ice-marginal lake classifications presented is freely available and thoroughly described in the form of a dataset description manuscript (How et al., 2025b). In addition, the production code for generating the dataset is available as an open and deployable Python package (How, 2025).

2.1.1 Direct lake classification

Ice-marginal lakes were automatically classified using two remote sensing methods to directly classify water bodies:

1. Backscatter thresholding classification from Sentinel-1 GRD (Ground Range Detected) dual-polarization C-band SAR (Synthetic Aperture Radar) imagery
2. Multi-spectral indices classification from Sentinel-2 MSI imagery

Averaged mosaics were derived from cloud- free (< 20 % maximum cloud cover), summer acquisitions (1 July to 31 August) for each year at a 10 m spatial resolution (Table 1 after smoothing to produce direct classifications of the presence of water. This threshold was trained for the detection of open water bodies (How et al., 2021). Four spectral indices were applied to Sentinel-2 MSI imagery to directly classify open water bodies (NDWI, MNDWI, AWEIsh, and AWEInsh), which use the blue (B2), green (B3) red (B4), near-infrared (B8), and the two shortwave infrared bands (B11, B12) (McFeeters, 1996; Xu, 2006; Feyisa et al., 2014). Thresholds for these indices were chosen based on previous studies, where a successfully classified pixel meets the threshold criteria of all indices (How et al., 2025b). The resulting dataset is a collection of vector delineations that represent the extent of each lake.

2.1.2 Indirect lake classification

In cases where automatic classification was not possible, two datasets were used as supplementary delineations; for example, in scenarios where a lake is persistently ice-covered. The first approach was to identify topographic sinks from the ArcticDEM mosaic (2 m spatial resolution) dataset (version 4.1), which is produced from optical stereo satellite imagery and manually

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selected from the best quality ArcticDEM strip data (Shean et al., 2016; Porter et al., 2018). Sinks were classified by identifying and filling depressions over a 50-pixel moving window and subsequently subtracting these from the original mosaic to produce an outline of a potential water body. These water bodies were then manually verified to confirm the presence of water within them.

The second approach was to integrate delineated water bodies from the Danish Climate Data Agency (Klimadatastyrelsen) Open Country Greenland 1:50,000 vector dataset (v3.1). Water bodies above a footprint size of 100 m^2 were digitised manually from high spatial resolution (0.5 m) commercial satellite imagery, with images collected during the summer months from 2017 to 2021 (Danish Climate Data Agency, 2024).

2.1.3 Lake filtering and curation

Lake outlines were filtered based on location to remove lakes that were not in contact with the ice margin. Specifically, the Danish Climate Data Agency ice margin from the Open Country Greenland 1:50,000 vector dataset (v3.1) was used to create a 1-km buffer around the ice margin, and lakes were retained if they were located within the buffer (Danish Climate Data Agency, 2024).

A size-based filter was applied to remove lakes below 0.05 km^2. This size threshold reflects the coarsest spatial resolution of the source imagery, that being the 10 m spatial resolution of Sentinel-1 and Sentinel-2 imagery (How et al., 2025b).

Retained lake outlines were manually inspected and edited for quality purposes. The purpose of this manual inspection was to remove mis-classifications, edit classified outlines (for example, in cases where shadowing effects were evident), remove lakes that did not hold water in specific years, remove lakes that were detached from the ice margin, and assign common lake identifications in cases where a lake was composed of several disconnected parts (How et al., 2025b). The common lake identifications were assigned based on lake area (largest to smallest) and correspond to all classified lakes across each time step from 2016 to 2025.

2.1.4 Lake size and abundance error estimation

A lake size error estimate was calculated by comparing outlines from the SAR backscatter and multi-spectral indices classification approaches (described in Section 2.1.1) to assess variability in footprint size (e.g. Leeson et al., 2013; Williamson et al., 2018; Moussavi et al., 2020; Lesi et al., 2022; Tom et al., 2022). Footprints were compared across each year (2016-2025) where both methods had successfully classified a lake.

On average, the two classification approaches produce a difference of 1.3 km^2, with a median difference of 0.16 km^2, and a summed difference of 514.6 km^2 ($\pm$ 3 %). This error is relatively consistent with lake size, with the central percentage error estimate varying between $\pm$ 1 % (for large lakes above 5.0 km^2) and $\pm$ 10 % (for small lakes below 0.2 km^2).

Given that the ice-marginal lakes used in this study were above a size of 0.05 km^2, an assessment was conducted to examine the number of ice-marginal lakes absent that were below this size threshold. Small lakes (< 0.05 km^2) were taken from the Danish Climate Data Agency inland water bodies vectors from Greenland (Danish Climate Data Agency, 2024). This dataset maps lakes from high resolution satellite imagery acquired between 2017 and 2021, where lakes up to 0.0001 km^2 (100 m^2)

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are supplied as point locations, and those above 0.0001 km^2 are supplied as polygons. Lakes smaller than 0.05 km^2 intersecting with the ice margin were extracted and then compared to the ice-marginal lake dataset presented in this study.

In total, 12,856 ice-marginal lakes below 0.05 km^2 were identified, which were absent from the study presented. These 12,856 lakes make up a total lake area of 101.6 km^2 (where an area of 0.0001 km^2 was assumed for lake point locations), which equates to only 2 % of the total area of the ice-marginal lakes presented here (4734.9 km^2), and therefore can be deemed as negligible on the findings presented.

2.2 Ice-marginal lake volume

2.2.1 Volume-area power law scaling

A non-linear volume-area (V-A) relationship was used to derive lake volume, as adopted in similar studies (e.g., Cook and Quincey, 2015; Shugar et al., 2020; Rick et al., 2023; Zhang et al., 2024b). The scaling model was calibrated using 102 GLOF-producing lake volumes. These GLOF-producing lake volumes were derived from co-registered ArcticDEM strip data coinciding with periods where each lake was drained and filled completely (Shean et al., 2016; Porter et al., 2018) (Figure A1a). The fitted power law was:

$$V = 0.0583A^{1.214} \tag{1}$$

This explained approximately 92 % of the variance in observed volumes in linear space (R^2 = 0.92; RMSPE = 0.25 km^3; Figure A1b), which was an improvement over the scaling model previously adopted in both global (e.g. Shugar et al., 2020) and regional studies (e.g., Cook and Quincey, 2015; Rick et al., 2023) when applied to the calibration lakes (Figure A1a). Residual ratios showed no strong trend with lake area, and 54 % of predicted volumes fell within a factor of two of the observed values (Figure A1c). The median prediction ratio was 1.6, so the model tends to overestimate individual lake volumes, more so for small lakes (< 0.5 km^2, median ratio 1.9) than for large lakes (1.4). This contrasts Shugar et al. (2020), who reported an RMSPE of 0.44 km^3 for their standalone non-linear scaling and ultimately required a two-regime split model to correct for small-lake under-prediction (<0.5 km^2).

A two-regime V-A relationship was explored to evaluate whether the scaling for small (< 0.5 km^2) and large (> 0.5 km^2) lakes needed to be represented differently, as adopted in previous glacial lake studies (e.g., Shugar et al., 2020; Rick et al., 2023). However, bootstrap resampling analysis showed that the coefficients for the small-lake V-A model were poorly constrained, whereas the coefficients for the large-lake V-A model converged on those obtained from the single power law (i.e. fitted to all calibration lakes). A single non-linear power law therefore provided a more statistically robust description of the observations.

2.2.2 Volume error estimation

Monte Carlo error estimation was carried out over 10,000 runs on the regional/total summed lake volumes, propagating:

1. Lake area uncertainty
2. Uncertainty in the fitted power law coefficients

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3. Residual model variance

This produced an uncertainty estimate of ± 26 %, which can be used when reporting regional and total summed lake volume. For instance, the absolute uncertainty for the reported total lake volume was ± 120.3 gigatonnes (Gt). Volumes for individual lakes should be used with caution, as the V-A power law scaling was resolved for regional and Greenland-wide lake volumes rather than individual lake volumes. Although the GLOF-producing lakes with observed volumes were adequately distributed across all regions of Greenland (Figure A1c), individual lake volumes may be outside the calibration limits of the model; with the limits being between 0.1 and 38.8 km^2 (due to data availability).

2.3 Ice-marginal lake surface temperature

2.3.1 Deriving summer surface water temperature

The average summer surface water temperature for each lake was derived from Landsat 8/9 OLI-TIRS (Operational Land Imager/Thermal Infrared Sensor) Collection 2, Level 2, surface temperature data; which is generated from descending, day-lit Landsat 8/9 thermal infrared band acquisitions (100 m spatial resolution) (NASA Applied Remote Sensing Training (ARSET) program, 2022; Malakar et al., 2018). Surface temperature estimates (LST_{land}) were corrected to freshwater surface temperature estimates (LST_{water}) using a calibration factor (Ermida et al., 2020; NASA Applied Remote Sensing Training (ARSET) program, 2022; Dyba et al., 2022; How et al., 2025b):

$$LST_{water} = (0.086 \times (LST_{land} \times 0.00341802 + 149.0) + 54.37) - 273.15 \quad (2)$$

Imagery was filtered by a maximum cloud cover of 20 %, with acquisitions only selected from the month of August. Unrealistic values below freezing (< 0 °C) were removed to reduce the influence of icebergs and ice cover. In total, surface water temperature estimates could be provided for 3240 lakes out of a possible 4038 lakes (i.e. 80 %).

2.3.2 Surface temperature error estimation

Remotely-sensed surface water temperature estimates were validated against all available in-situ surface (≤ 5 m) measurements in Greenland (Figure A2). In situ measurements were provided exclusively from lakes in southwest Greenland, reflecting the sparseness of observations currently. These are:

1. Kangerluarsunnguup Tasia (also known as Badesø), 2011-2026 (64°7’47"N, 51°22’1"W) (Greenland Ecosystem Monitoring, 2026)
2. Qaasi-Sø, 2011-2026 and 2024 (64°9’3"N, 51°18’46"W) (provided by Greenland Ecosystem Monitoring, 2026 and Asiaq Greenland Survey, respectively)
3. Russell Lake, 2023-2024 (67°8’10"N, 50°4’52"W) (provided by the Greenland Integrated Observing System (GIOS) programme)

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4. Qamanersuaq, 2024 (63°28’37"N, 50°0’18"W) (provided by Asiaq Greenland Survey)

5. Asiaq hydrological monitoring station 924, 2024 (62°54’47"N, 49°49’59"W) (provided by Asiaq Greenland Survey)

6. Motzfeldtip Tasia, 2024-2025 (61°9’19"N, 44°58’36"W) (Vacek et al., 2026)

The comparison yielded a strong correlation of 0.93, with an RMSE of 1.2 °C and an error estimate of ± 1.0 °C (based on the average difference in temperature) (Figure A2). This trend is consistent regardless of the time of year of acquisition/measurement, with all observations collected during coinciding Landsat 8/9 overpasses between 13.00-15.00 UTC.

2.4 GLOF occurrences

GLOF occurrence data was sourced from the Greenland-wide GLOF inventory presented in Dømgaard et al. (2024a) and Dømgaard et al. (2024b). Fluctuations in lake water levels were derived using altimetry datasets from ICESat/GLAS (Zwally et al., 2014), IceBridge ATM (Studinger, 2010, 2013) and ICESat-2 (Smith et al., 2023) between 2003 and 2023. Outliers in the time-series for each lake water level were removed using the median water level, removing data that were outside a set threshold outside the median absolute deviation (MAD). Lakes with GLOF behaviour were defined as those with a maximum water level difference that exceeded 4 m, and showed an abrupt decline in water level between two successive observations recorded within the same year. These were also verified manually. Validation from manual inspection of optical images (Planet Scope, Sentinel-2 and Landsat 8-9) revealed an error estimate of ± 5 %, with 95 % of detected GLOFs confirmed by the validation.

3 Results

A cumulative total of 4038 ice-marginal lakes were identified across Greenland from 2016 to 2025, ranging in area from 0.05 km^2 (i.e. the minimum extent) and 131.7 km^2 at the ice sheet margin and the margins of PGICs (Figure 1a). The largest lake extent is an unnamed lake at the ice sheet margin in the northern region (NO), with the ten largest lakes (between 54.9 and 131.7 km^2) present in the NO, northeast (NE) and southwest (SW) regions. The cumulative mapped extent of ice-marginal lakes is 4734.9±514.6 km^2, where all lake surface areas are summed together. The largest summed areas evident in the NE (1428.0 km^2), SW (1388.5 km^2) and NO (1012.0 km^2) regions (Table A1).

GLOFs have been identified at 318 of the ice-marginal lakes identified (Figure 1b). Of these GLOF-producing lakes, 266 are adjacent to the ice sheet margin and 52 are adjacent to the margins of PGICs. The highest number of GLOF-producing lakes are present in the NE (98) and NO regions (77), and the SE region has the lowest number, being only 3 (Table A1). The largest GLOF-producing lake is an unnamed lake (Lake ID 20) in the NO region, with an area of 39.2 km^2, followed by Tininnilik in the CW region (38.8 km^2) and Iluliallup Tasia in the SW region (36.0 km^2).

Average summer surface temperatures at these lakes follow a latitudinal trend, where lakes are warmer in more southerly regions on average, and colder in higher latitude regions (Figure 1c). For example, average summer surface temperatures are

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6.3±1.0 °C and 6.6±1.0 °C in the southeast (SE) and SW regions; whereas these are 2.9±1.0 °C, 3.2±1.0 °C and 4.5±1.0 °C in the NE, NO and northwest (NW) regions, respectively (Table A1).

Ice-marginal lakes across Greenland hold a total of 462.5±120.3 Gt (or km^3). Over three-quarters of this volume (83 %) is held in lakes adjacent to the Ice Sheet (Table A1). The SW and NE regions have the largest summed volume, being 143.9±37.4 Gt and 143.2±37.2 Gt, respectively (Figure 1d). The summed volume for GLOF-producing lakes is 67.0±17.4 Gt, which suggests that 14 % of meltwater stored at Greenland's terrestrial margins is exceptionally dynamic (i.e. changing very abruptly) and 86 % is relatively stable (i.e. unchanging and/or slowly changing).

The annual number of ice-marginal lakes identified between 2016 and 2025 ranged from 2861 to 3554, with lakes at both ice sheet and PGIC margins following similar fluctuations (Figure 2a and 2c). These annual counts are lower than the cumulative total of 4038 unique lakes, reflecting temporal turnover in the lake population as individual lakes form, detach from the ice margin or disappear between years. Therefore, although the annual number of lakes remained relatively stable, the individual lakes comprising this population were not necessarily persistent throughout the study period. No linear or consistent trends were evident in the annual number of lakes over time. The NE and SW regions showed the largest changes, fluctuating by 243 and 229 lakes, respectively, reflecting the higher number of lakes and larger total lake areas in these regions.

The total lake area (i.e. the sum of all lake surface areas) fluctuated by 1259.5±37.8 km^2 across all regions, with the largest fluctuations evident at lakes in the SW region located at the ice sheet margin (Figure 2a) and at lakes in the NE region located at the margins of PGICs (Figure 2c). The median lake area remained consistent throughout the decade, with the median for all lakes remaining between 0.2 and 0.3 km^2. This consistency in median lake area was reflected regionally, except for lakes at the ice sheet margin in the CE region (Figure 2a). A notable jump in median lake area is apparent in the CE region, adjacent to the ice sheet margin, in 2022 (0.4 km^2). This is due to a sampling bias in the dataset, rather than a true signal of lake size. The sampling bias is caused by poor classification coverage due to cloud cover in 2022, which created an artificially elevated median area.

The rate of change in lake area was calculated using linear regression analysis to reveal that the areas of 1518 lakes remained unchanged in the last decade (i.e. with lake area change limited to ± 0.05 km^2 yr^{-1}) (Table A2). This equates to 87 % of ice-marginal lakes in Greenland where rate of change analysis could be conducted, and a total surface area of 1265.9±40.0 km^2. 61 lakes (4 %) increased in size over time, with a total surface area of 557.8±16.7 km^2. 164 lakes (9 %) decreased in size, with a total surface area of 2095.9±62.9 km^2. The type of margin (ice sheet or PGIC) has little impact on the spread of these groupings – at the ice sheet margin, 4 % of lakes grew, 11 % were shrinking and 84 % remained the same (Figure 2b); whilst at the margins of PGICs, 3 % of lakes grew, 5 % were shrinking and 93 % remained the same.

The average summer surface temperature estimates for all identified ice-marginal lakes fluctuated between 3.1±1.0 °C (2018) and 4.7±1.0 °C (2023), with the median following a similar pattern (Figure 3a). These fluctuations do not indicate a clear linear trend in average summer surface temperature over time. Regression analyses indicate that change in surface temperature is not strongly influenced by lake area alone, showing no statistically significant relationship (R^2 = 0.11) (Figure 3b). Lake location is associated with temperature, with lower average temperatures observed at higher latitudes in general (Figure 1c). However, this trend is not reflected in the rate of change in temperature, where a weak but consistent north-to-

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south gradient is evident (Figure 3c). When partitioned by regions grouped by coast, marked differences are evident with lakes on the east coast generally warming fast and lakes on the west coast having higher variance (Figure 3d). In summary, lake size, latitude and coast explain only a limited proportion of the observed variance in surface temperature trends (R^2 = 0.31).

4 Discussion

4.1 Decadal changes in ice-marginal lakes conditions

Variability in annual ice-marginal lake conditions is evident between 2016 and 2025, measured by the number of lakes and lake surface area. The annual number of ice-marginal lakes fluctuate marginally, with the largest variations in the NE and SW regions. This indicates stability in ice-marginal lake abundance over the 10-year monitoring period. It is likely that this stability is because while enhanced retreat does occur at terrestrial ice margins (i.e. not marine-terminating outlets), it is not pronounced enough to disconnect existing lakes or to have retreated into new over-deepenings over decadal timescales (Mallalieu et al., 2021).

Most lakes (87 %) show negligible rates of change ($\pm$ 0.05 km^2 yr^{-1}). However, lakes experiencing declining area (> -0.05 km^2 yr^{-1}) collectively account for 2095.9 km^2, which is equivalent to 53 % of the total summed lake area. This indicates that, despite most lakes exhibiting negligible changes in area, a substantial proportion of the total lake area is associated with lakes experiencing decline. Changes in lake area are disproportionately represented in terms of total area relative to the number of lakes affected. This suggests that while ice-marginal lakes are relatively stable in number over decadal timescales, changes in lake area can be substantial when considered across Greenland. These findings provide important context for investigating glacier-lake interactions in Greenland. Previous studies have largely focused on local or regional studies in the SW region (e.g. Carrivick and Quincey, 2014; Mallalieu et al., 2021; Kjeldsen et al., 2014, 2017), and adopted a binary distinction between lake-terminating and land-terminating glaciers (e.g. Holt et al., 2024), or between lake-terminating and marine-terminating glaciers (e.g. Vacek et al., 2026). Such approaches have demonstrated that the presence of a lake at the glacier terminus enhances ice flow and terminus retreat (Harpur et al., 2026). As previous studies have largely focused on decadal timescales, the longer-term evolution of ice-marginal lakes and its influence on glacier dynamics remain comparatively understudied. This highlights the need to consider lake evolution over multi-decadal timescales to better understand the changing interactions between lakes and glaciers.

4.2 Spatially variable controls on lake surface temperature change

Average ice-marginal lake surface temperatures exhibit a clear spatial pattern, implying an atmospheric influence (Figure 1c). However, no consistent temporal trend in temperature change is observed between 2016 and 2025. Instead, weak but coherent relationships emerge, with lake size, latitude and coast exerting a minor influence on temperature variability (Figure 3). Larger lakes at higher latitudes show a slight tendency towards reduced warming, although these relationships explain only a small proportion of the overall variance.

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This weak signal likely reflects the influence of short-term and seasonal processes on lake thermal structure. Observations from Carrea et al. (2025) demonstrate that ice-marginal lakes in Greenland experience pronounced seasonal asymmetry, characterised by rapid surface warming following ice-free conditions and more gradual cooling towards ice cover formation. Such dynamics introduce substantial intra-seasonal variability, which may obscure longer-term trends when using temporally averaged datasets.

Although this study attempts to minimise these effects by limiting temperature estimates to August observations, variability in acquisition timing and local conditions likely persists; such as delayed ice-off in shaded areas or at higher latitudes. Consequently, the limited explanatory power of the analyses reflects not only weak climatic or geographic controls, but also the challenge of resolving true surface temperature trends from temporally sparse observations. This highlights the need for higher temporal resolution datasets to better capture the thermal evolution of ice-marginal lakes.

4.3 Using change in lake area as a proxy for lake volume

Between 2016 and 2025, ice-marginal lakes in Greenland cover a cumulative total extent of 4734.9 km^2. Using empirically fitted V-A scaling, the lakes hold a total volume of 462.5 Gt (Figure 1d). V-A scaling has been used to estimate lake volume in recent studies, taking the form of log-log linear scaling for smaller lakes (< 0.5 km^2) and non-linear power scaling for larger lakes ($\geq$ 0.5 km^2) to produce volume estimates in regions where in situ bathymetry measurements are sparse (e.g. Rick et al., 2023) and enable consistent, large-scale volume assessments (e.g. Shugar et al., 2020; Zhang et al., 2024b). A key assumption underlying these scaling approaches is that lake area scales predictably with volume, and changes in lake area can act as a proxy for volume change.

The Greenland-specific V-A relationship developed here provides a substantial improvement over previously published relationships, explaining 92 % of the variance in lake volume and most estimated volumes within a factor of two of observations (Figure A1). These results indicate that, despite the inherent variability in lake basin morphology, lake area provides a useful first-order predictor of volume across the range of lakes represented in the calibration dataset.

The resulting Greenland-wide estimate of 462.5 Gt is higher than the 397.8 Gt estimated by Zhang et al. (2024b) (Figure 4), highlighting the importance of using regionally appropriate scaling relationships when estimating lake volume. Although differences in calibration data and methodology may contribute to this discrepancy, the improved agreement between the Greenland-specific relationship and observed lake volumes suggests that regional calibration can provide a valuable basis for large-scale assessments where direct bathymetric observations are limited. Some individual lakes nevertheless deviate substantially from the empirical relationship. Such outliers have also been identified in previous studies (e.g. Cook and Quincey, 2015) and may reflect complex basin geometries, including over-deepenings formed during glacier retreat, as well as variations in sedimentation rates (Veh et al., 2026). Overall, the results demonstrate that empirical V-A relationships can provide a useful and scalable basis for first-order assessments of ice-marginal lake storage across Greenland, while also highlighting where their predictive capacity can be improved.

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4.4 The significance of ice-marginal lakes as a terrestrial storage of meltwater across Greenland

Between 2016 and 2025, a cumulative total of 4038 ice-marginal lakes have been identified, collectively covering 4734.9 km^2 and storing an estimated 462.5 Gt of meltwater (Figure 1). Global inventories show greater divergence, with Song et al. (2025) identifying 2826 ice-contact lakes ($\geq$ 0.05 km^2) with a combined area of 2957.0 km^2, and Zhang et al. (2024b) identifying 5926 ice-contact lakes with a combined area and volume of 6535.3 km^2 and 397.8 Gt, respectively (Figure 4, Table A3). This comparison indicates that methodology, and temporal coverage and spatial resolution of the source data substantially influence both lake counts and total area.

The significance of ice-marginal lakes is further highlighted when considered in the context of ice and meltwater discharge. Ice-marginal lakes occupy approximately 10 % of the Greenland Ice Sheet margin and occur adjacent to 5 % of PGICs. The total volume of lakes adjacent to the Greenland Ice Sheet is 383.5 Gt, which is almost three times larger than the average annual mass loss (ca. -155 Gt) from the reference period 1991 to 2020 (Mankoff et al., 2021). In addition, the mean ice discharge into ice-marginal lakes is estimated to be 4.9 Gt yr^{-1} (Carrivick et al., 2022). This signifies that the total lake storage identified here represents a substantial reservoir of meltwater. However, as the inter-comparison of datasets shows (Figure 4), the magnitude of this storage and its perceived role within Greenland, and the wider global cryosphere system, is sensitive to methodological choices in lake classification.

An important distinction lies in how much of this storage is stable versus that episodically and abruptly released. The results presented here indicate that most meltwater storage in ice-marginal lakes is relatively unchanging. Therefore, the most significant short-term changes are associated with episodic drainage events, i.e. those producing GLOFs. Of the ice-marginal lakes identified in this study, 318 are known to have experienced GLOFs, holding a total volume of 67.0 Gt. This implies that approximately 14 % of total meltwater storage at Greenland's terrestrial margins is dynamic and subject to abrupt release. However, this is likely a conservative estimate, consistent with previous assessments. In addition, this estimate assumes complete drainage of these lakes, whereas many GLOF-producing lakes have been observed to drain only partially and GLOFs do not necessarily occur on a consistent basis (e.g., Dømgaard et al., 2023; Dømgaard et al., 2024a; Binder et al., 2026)

The occurrence of GLOFs has been linked to periods of extreme runoff, such as during the 2019 melt season, characterised by anomalously warm and dry conditions, reduced surface albedo, and enhanced melt across the Greenland Ice Sheet (Dømgaard et al., 2024a). Future projections indicate that such events may become more frequent, driven by increasing interannual variability in runoff and progressive ice thinning (e.g. Kjeldsen et al., 2017; Goelzer et al., 2020; Slater et al., 2021). As a result, while ice-marginal lakes act as substantial reservoirs of meltwater, GLOF-producing lakes hold a disproportionate contribution of dynamic storage that is intermittently released on short timescales. GLOF-producing lakes therefore represent a critical, yet highly variable, pathway for transferring meltwater from terrestrial margins to the ocean, with important implications for sea-level contribution, ice dynamics, and downstream geomorphological and ecological systems.

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5 Conclusions

Ice-marginal lakes have been revealed to be a substantial reservoir of meltwater surrounding the Greenland Ice Sheet and Greenland's PGICs, with 4038 lakes covering 4734.9 km^2 and storing an estimated 462.5 Gt. This represents approximately 1 % of Greenland's ice-free land, highlighting their importance within the terrestrial proglacial environment. Inter-comparison with existing datasets indicates that estimates remain sensitive to methodological choices (such as temporal and spatial resolution, and scaling approach), and should therefore be applied with caution; especially when used on specific lakes and catchments.

Regionally, the SW and NE regions contain the greatest number of lakes and the largest cumulative area and volume, as well as the highest variability between 2016 and 2025. However, median lake area has remained relatively stable (0.2-0.3 km^2), with negligible rates of change ($\pm$ 0.05 km^2 yr^{-1}) over the period. This suggests that terrestrial ice-margin retreat is insufficient to systematically expose new over-deepenings or drive widespread lake expansion over decadal timescales, and on a regional- and Greenland-wide spatial scale. Similarly, temporal trends in lake surface temperature estimates are weak despite a clear latitudinal trend with higher latitude lakes generally experiencing colder surface temperatures. Lake size and location exert only minor controls on temperature change, highlighting the strong influence of inter-annual variability and the difficulty of resolving trends from temporally sparse observations.

A key finding from this study is the distinction between relatively stable and dynamic meltwater storage at Greenland's ice margins. Of the lakes identified, 318 have experienced GLOFs, and these lakes collectively account for 67.0 Gt (14 %) of the total estimated meltwater storage in Greenland. These insights show that ice-marginal lakes represent a heterogeneous component of the Greenland meltwater system, characterised by both relatively stable storage and episodic, high-magnitude release. Although the temporary storage of meltwater in lakes is unlikely to substantially alter its eventual contribution to global sea level, the timing and rate of its delivery to the ocean may be influenced by lake drainage dynamics. In particular, GLOFs can result in rapid, episodic freshwater contribution, which may not be adequately represented in future sea level projections as they do not explicitly account for ice-marginal lake storage and drainage. Accurately resolving these processes is critical for constraining terrestrial meltwater storage, in particular the timing of freshwater release and contribution to sea-level change.

Code and data availability. The ice-marginal lake dataset presented here is available on the GEUS Dataverse (How et al., 2025a). This dataset includes lake surface area, abundance, summer water surface temperature and GLOF occurrences. The software for producing this dataset is open source and peer reviewed (How, 2025).

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Competing interests. The contact author declares that none of the co-authors have any competing interests

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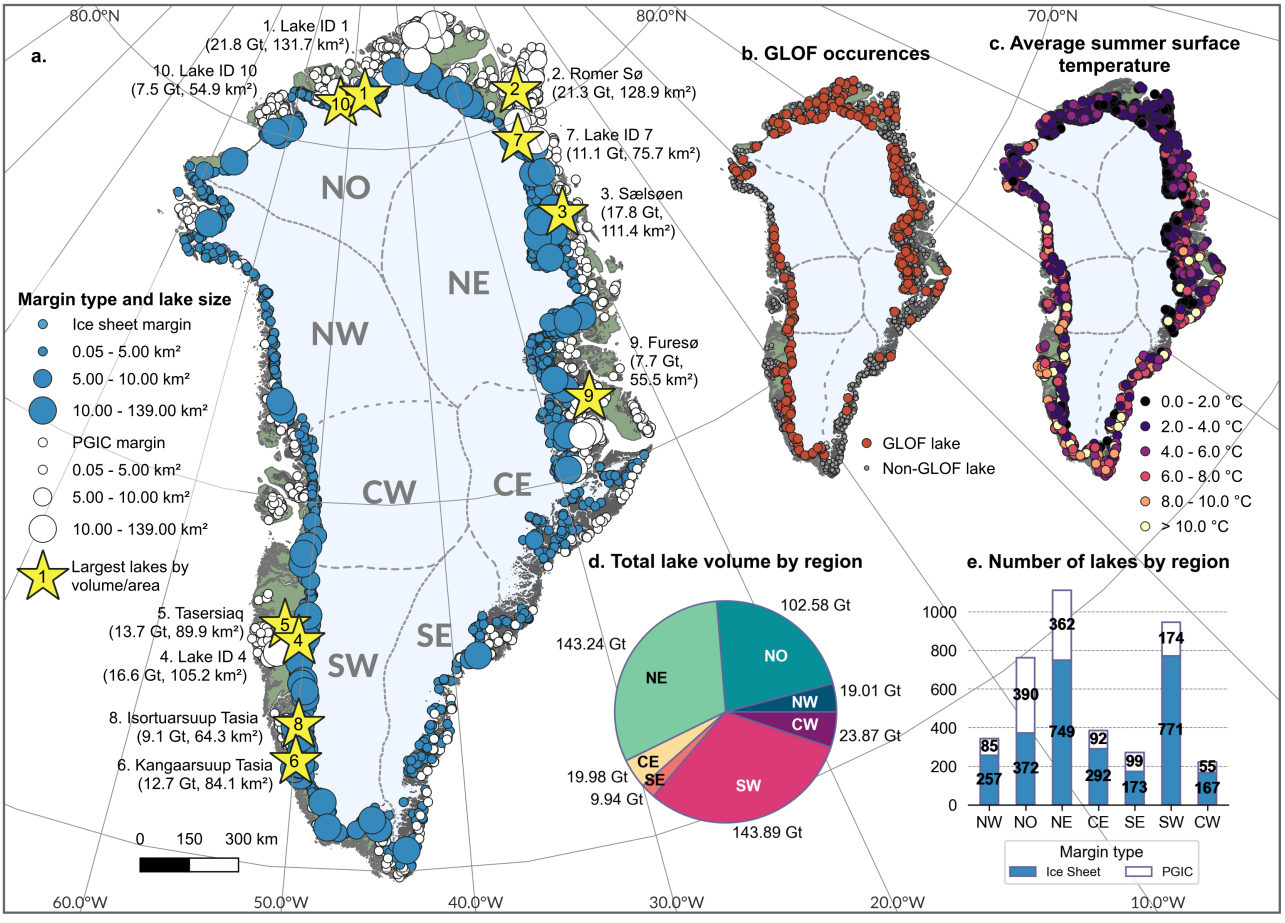


Figure 1. An overview of ice-marginal lakes across Greenland from 2016 to 2025, mapping lakes by margin type and size (a), lakes with known GLOFs (b), average summer surface temperature (c), summed lake volume by region (d), and the number of lakes within each region (e). Values correspond to statistics from 2016 to 2025 on an annual basis, which are also provided in Table A1. Starred locations in (a) denote the ten largest lake extents, which are annotated with lake name and area (km^2). Base maps are provided by Danish Climate Data Agency (2024), and region delineations are provided by Mouginot and Rignot (2019).

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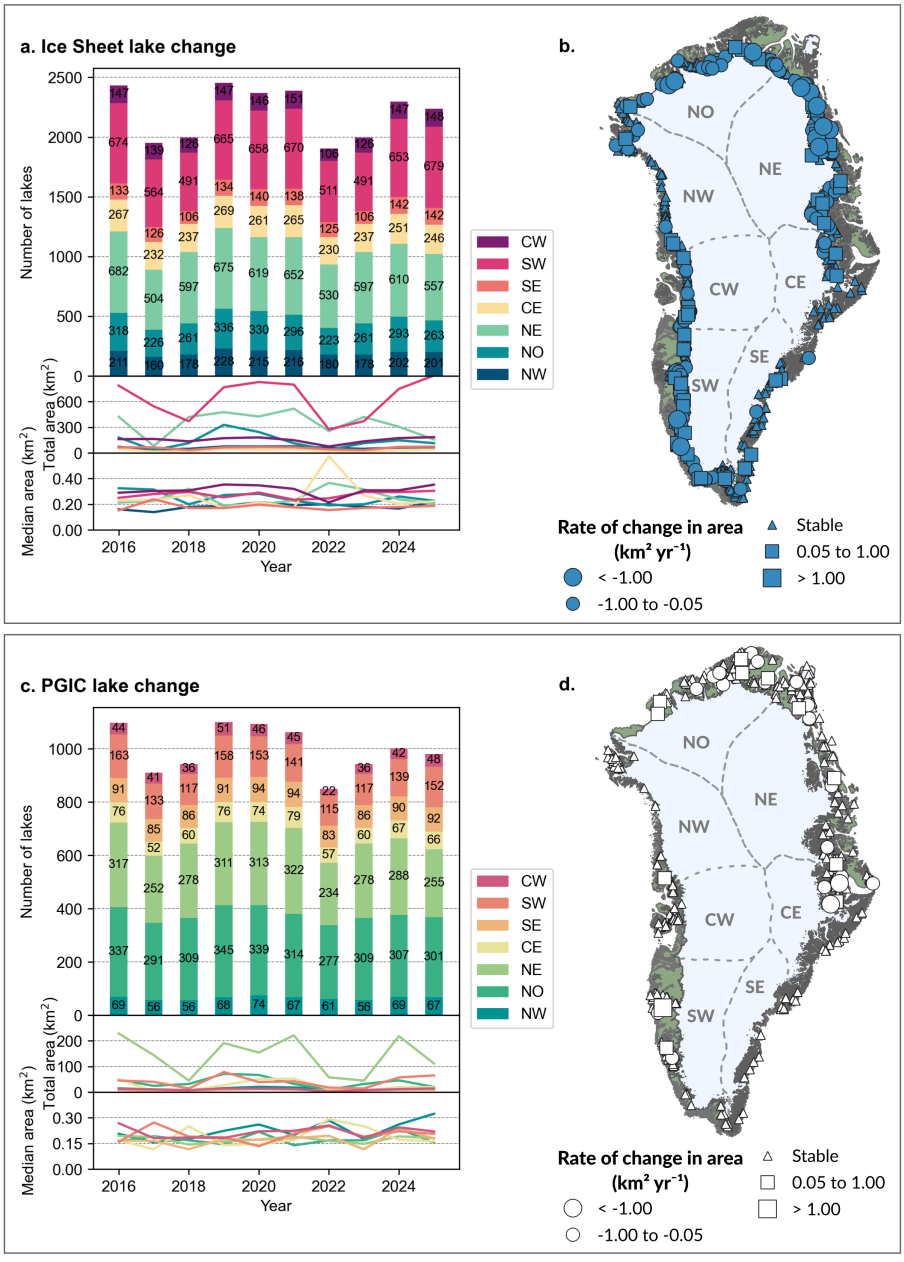


Figure 2. Changes in ice-marginal lakes from 2016 to 2025, divided by margin type (ice sheet and PGIC) and region (CW, SW, SE, CE, NE, NO and NW). Changes in abundance (top plot), total (i.e. summed) area (middle plot) and median lake area (bottom plot) are presented for lakes adjacent to an ice sheet margin (a) and a PGIC margin (c). The rate of change in lake area is calculated based on a linear regression of lake area over an annual temporal resolution, where (b) presents lakes adjacent to an ice sheet margin and (d) presents lakes adjacent to a PGIC margin. Circle symbols indicate lake shrinkage, triangle symbols indicate stable lakes (i.e. a change of less than 0.05 km^2, and square symbols indicate lake growth. Base maps are provided by Danish Climate Data Agency (2024) and region delineations are provided by Mouginot and Rignot (2019).

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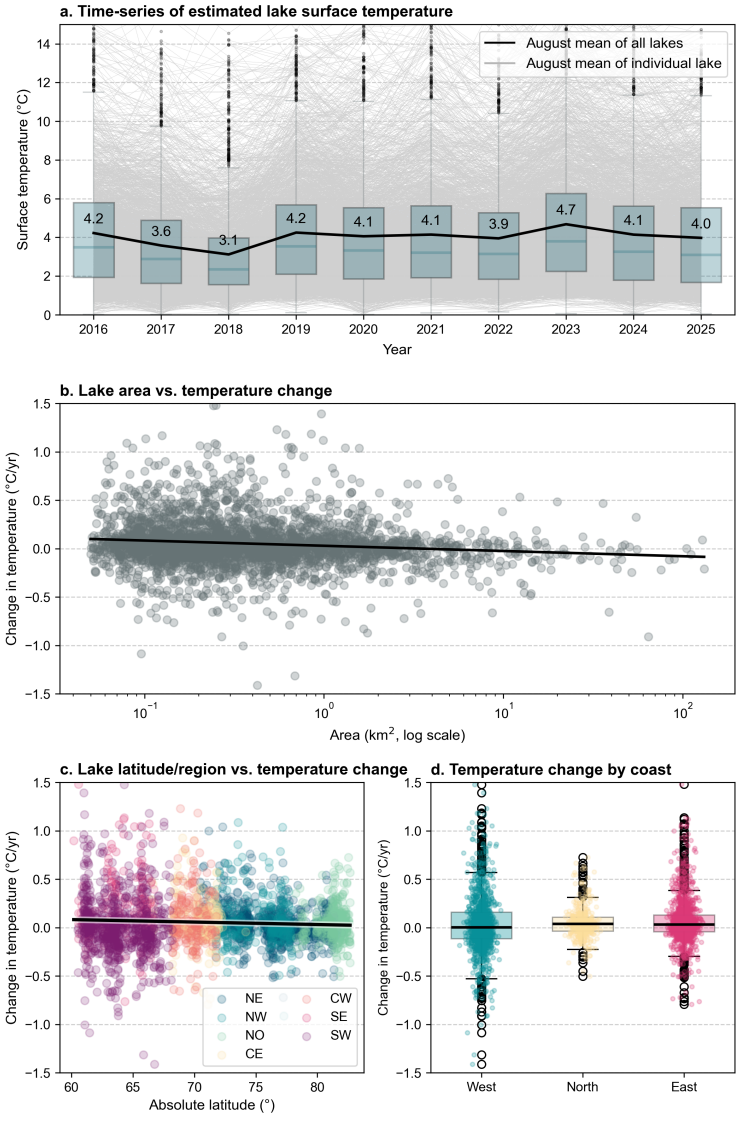


Figure 3. Change in average summer surface temperature at ice-marginal lake across Greenland from 2016 to 2025. The top plot (a) shows average summer lake surface temperatures over annual time steps, with results for both individual lake temperatures (grey) and averages of all lakes (black). Boxplots (blue) indicate the median and interquartile range (25-75 %). Mean values for each annual time step are annotated over each box plot, along with a corresponding trend line (black). Change in temperature (°C yr^{-1}) is plotted against lake area (b), lake latitude (c) and coast (d), with each point representing one lake and regression lines overlaid. Average summer surface temperatures are calculated from all available scenes acquired from the month of August to limit the risk of mis-estimates due to ice-covered conditions. Additionally, all estimates below 0 °C have been removed.

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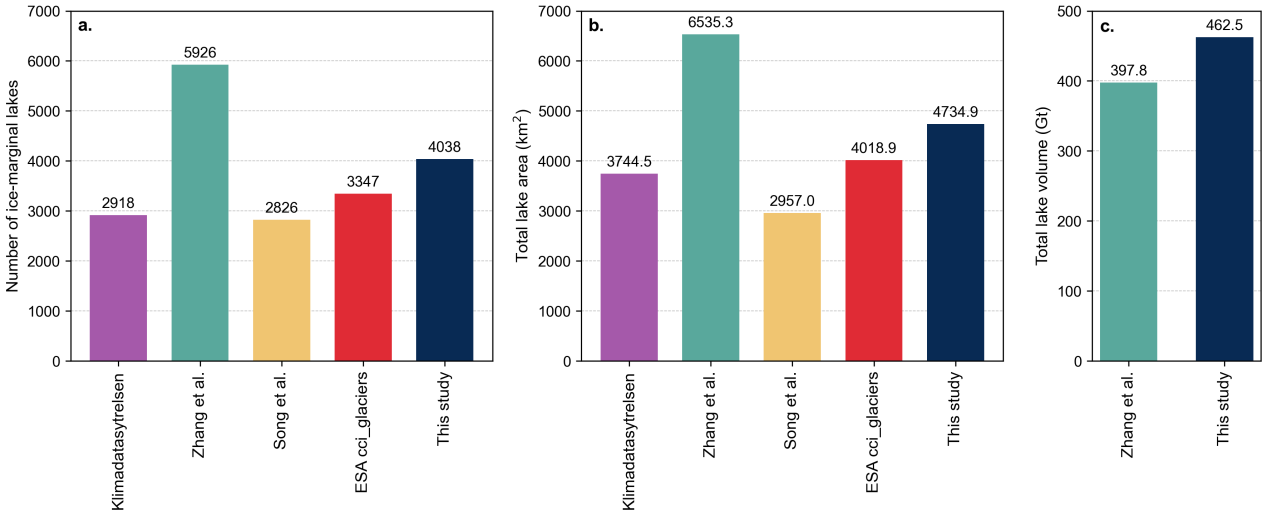


Figure 4. Comparison of lake abundance (a), total lake area in km^2 (b) and total lake volume in gigatonnes (c) from existing glacial lake datasets. The existing glacial lake datasets consist of Klimadatastyrelsen Open Country Greenland 1:50,000 dataset (Danish Climate Data Agency, 2024; purple), the Global Glacial Lake dataset (Zhang et al., 2024b; turquoise), the GIGLake (Global Inventory of Glacial Lakes) dataset (Song et al., 2025; yellow), the ESA Glaciers Climate Change Initiative (Glaciers_cci) 2017 inventory of ice marginal lakes in Greenland (Wiesmann et al., 2021; How et al., 2021; red), and the dataset presented in this study (dark blue). In all cases, the glacial lake datasets have been filtered to strictly ice-contact lakes over 0.05 km^2 to facilitate direct comparison. Corresponding values are provided in Table A3.

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Table 1. Summary of automatic lake classification approaches

Satellite	Imagery	Acquisition filters	Timespan	Pre-processing routines	Classification approaches	Threshold	Classification target
Sentinel-1	GRD (Ground Range Detected) dual-polarization C-band SAR 10-m images	Interferometric Wide Swath (IW) HH polarisation 20% max cloud cover	1 July–31 August 2016–2025	Calibrated, ortho-corrected averaged scenes 50-m focal median smoothing	Static backscatter threshold	< -20	Direct classification of open water bodies
Sentinel-2	MSI, TOA Level 1C 10-m images	20% max cloud cover	1 July–31 August 2016–2025	Opaque and cirrus cloud masking	NDWI (Normalised Difference Water Index)	< 0.3	Open water with shadowing
					MNDWI (Modified Normalised Difference Water Index)	> 0.1	Snow/ice in water
					AWEIsh (Automated Water Extraction Index with shadow)	> 2000 and < 5000	Sediment-loaded water without shadowing
					AWEInsh (Automated Water Extraction Index without shadow)	> 4000 and < 6000	Sediment-loaded water with shadowing

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Table 2. Lake areas and volume estimates for the ten largest ice-marginal lakes extents in Greenland

Lake name	Region	Margin type	Max. area (km^2)	Max. volume (Gt)
Lake ID 1	NO	Ice Sheet	131.7	21.8
Romer Sø	NE	PGIC	128.9	21.3
Sælsøen	NE	Ice Sheet	111.4	17.8
Lake ID 4	SW	Ice Sheet	105.2	16.6
Tasersiaq	SW	Ice Sheet	89.9	13.7
Kangaarsuup Tasersua	SW	Ice Sheet	84.1	12.7
Lake ID 7	NE	Ice Sheet	75.7	11.1
Isortuarsuup Tasia	SW	Ice Sheet	64.3	9.1
Furesø	NE	PGIC	55.5	7.7
Lake ID 10	NO	Ice Sheet	54.9	7.5

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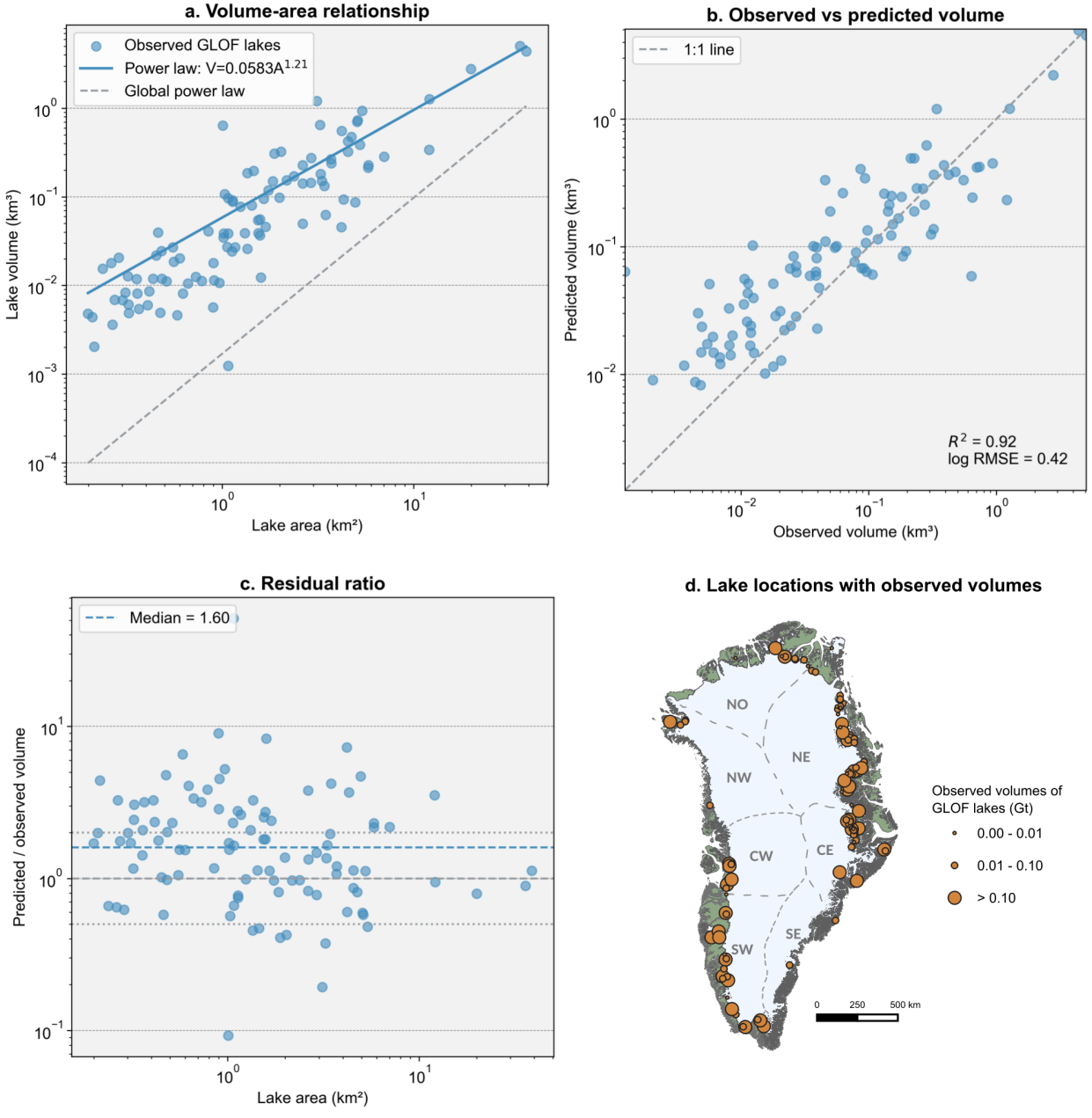


Figure A1. Evaluation of the empirical V-A relationship used to estimate the volume of ice-marginal lakes. (a) Observed GLOF-producing lake volumes derived from ArcticDEM strip differencing plotted against lake surface area, together with the best-fitting non-linear power-law relationship and a previously published global area–volume relationship (Shugar et al., 2020; Rick et al., 2023) for comparison. (b) Comparison between observed and model-predicted lake volumes, with the dashed line indicating the 1:1 relationship. (c) Prediction ratio (predicted/observed volume) as a function of lake area. The dashed horizontal line indicates unbiased predictions (ratio = 1), while the dotted lines indicate a factor-of-two over- and under-prediction. (d) Locations of the GLOF-producing lakes with observed volumes, with point size denoting the observed volume in gigatonnes (Gt).

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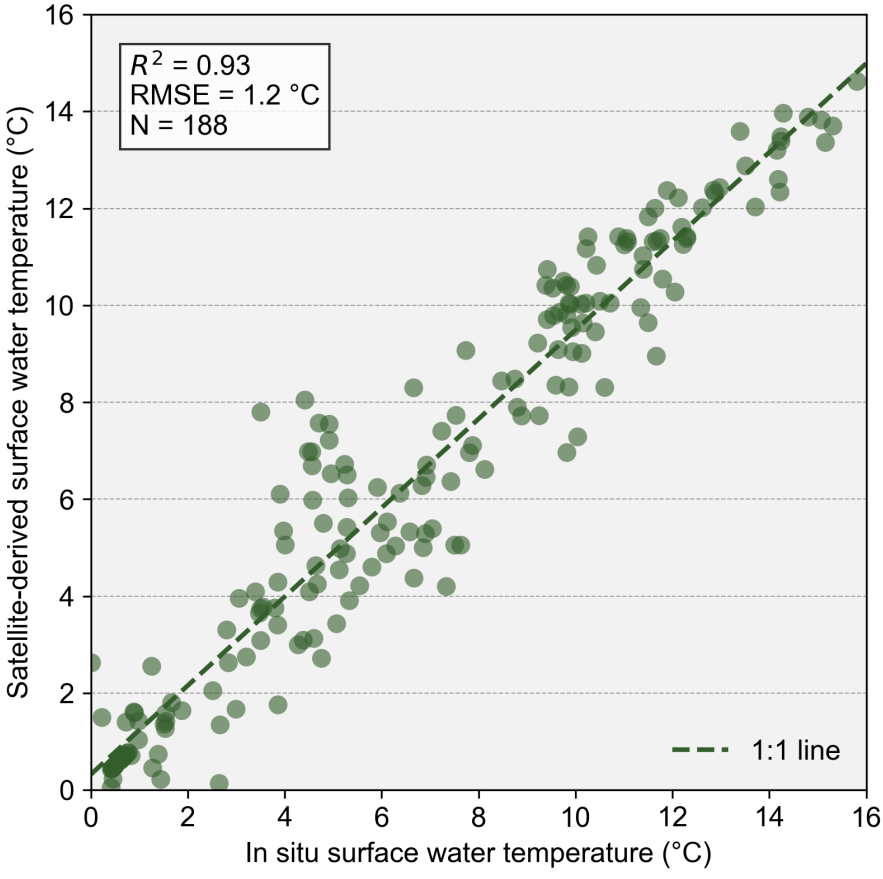


Figure A2. Remote sensed temperature estimates compared to in situ surface (≦5 m) water temperature measurements (°C), where one point represents one comparison measurement. The dashed line represents a linear 1:1 fit. The comparison is from lakes in southwest Greenland where in situ observations are available – Kangerluarsunnguup Tasia, Qassi-Sø, Russell Lake, Qasmanersuaq, Asiaq station 924 and Motzfeldtip Tasia (How et al., 2025b).

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Table A1. Descriptive statistics on ice marginal lakes by region and margin type

Region	Number			Volume (Gt)			Area (km^2)		
	IS	PGIC	All	IS	PGIC	All	IS	PGIC	All
All regions	2781	1257	4038	383.5	79.0	462.5	3845.0	889.9	4734.9
CE	292	92	384	12.7	7.2	20.0	182.8	83.7	266.5
CW	167	55	222	22.7	1.1	23.8	242.6	20.4	262.9
NE	749	362	1111	103.3	39.9	143.2	1070.2	357.9	1428.0
NO	372	390	762	86.0	16.5	102.6	779.2	232.8	1012.0
NW	257	85	342	16.1	2.9	19.0	192.7	47.5	240.2
SE	173	99	272	8.5	1.5	9.9	108.2	28.5	136.7
SW	771	174	945	134.1	9.8	143.9	1269.4	119.1	1388.5

Region	Median area (km^2)			GLOFs			Temp (°C)		
	IS	PGIC	All	IS	PGIC	All	IS	PGIC	All
All regions	0.3	0.2	0.2	266	52	318	4.4	4.8	4.5
CE	0.2	0.2	0.2	39	2	41	4.1	5.0	4.3
CW	0.3	0.2	0.3	18	1	19	5.6	6.7	5.9
NE	0.3	0.2	0.3	86	12	98	2.9	3.8	3.2
NO	0.4	0.2	0.2	47	30	77	2.7	3.2	2.9
NW	0.2	0.3	0.2	20	5	25	4.4	4.7	4.5
SE	0.2	0.2	0.2	3	0	3	6.3	7.0	6.6
SW	0.3	0.2	0.2	53	2	55	6.1	7.0	6.3

[a]IS = Ice Sheet; PGIC = Periphery Glaciers and Ice Caps; Regions based on Mouginot and Rignot (2019).

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Table A2. Regional statistics on rate of lake area change

Region	Number of lakes grown			Number of lakes shrunk			Number of lakes stable		
	Ice Sheet	PGIC	All	Ice Sheet	PGIC	All	Ice Sheet	PGIC	All
All regions	49	12	61	142	22	164	1075	443	1518
CE	2	1	3	7	4	11	58	31	89
CW	5	0	5	11	0	11	93	38	131
NE	11	3	14	47	7	54	218	134	352
NO	5	5	10	31	8	39	136	91	227
NW	3	1	4	7	0	7	118	47	165
SE	4	0	4	3	0	3	71	27	98
SW	19	2	21	36	3	39	381	75	456

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Table A3. Summary of glacial lake dataset comparison

Dataset source	Lakes reported in Greenland			Strictly ice-contact lakes over 0.05 km^2		
	Number	Total area (km^2)	Total volume (Gt)	Number	Total area (km^2)	Total volume (Gt)
Klimadatastyrelsen (2024)	156,593	14,337.3	-	2918	3744.5	-
Zhang et al. (2024)	14,845	6683.1	398.5	5926	6535.3	397.8 [a]
Song et al. (2025)	48,307	10,681.8	-	2826	2957.0	-
How et al. (2021)	-	-	-	3347	4018.92	-
This study	-	-	-	4038	4734.9	462.5

[a] An additional time step for 1990 is also available with the Global Glacial Lake dataset provided by Zhang et al. (2024), but only the 2020 time step was used here.