Living Planet Fellowship

FINAL REPORT

Investigating Greenland's ice marginal lakes under a changing climate (GrIML)

Penelope How

Geological Survey of Denmark and Greenland (GEUS)

Prepared by	**Penelope How**
Approved by	**Signe Bech Andersen & Andreas Ahlstrøm**
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1 EXECUTIVE SUMMARY

This final report signifies the ending of the GrIML project, where two clear sets of work have been identified and developed:

1. A comprehensive inventory series of ice marginal lakes from 2016 to 2023, classified with a mutli-sensor approach based on established remote sensing methodologies
2. The development of individual ice marginal lake time-series analyses to explore their influence in different settings around Greenland that are scientifically and/or societally relevant

These outputs contribute to assessing Greenland's terrestrial water storage and its implications for glacier dynamics, hydropower planning, and ecological studies. Ultimately, the datasets and findings produced will further our understanding of future sea level contribution from the Greenland Ice Sheet, with the ice marginal lake inventory series being a step forward in addressing limitations in the terrestrial (i.e. off-ice sheet) storage of meltwater. The project outcomes are openly available in a set of peer-reviewed (and in prep) publications, alongside an open and reproducible data production workflow that will foster future scientific and societal applications.

2 OBJECTIVES AND WORKPLAN

This final report represents the end of Phase 4, and the end of the GrIML project according to the proposed project timeline (Figure 1). By the end of Year 2, the following objectives should be completed:

a. A series of ice marginal lake inventories should have been generated, which cover the Sentinel-era between 2017 and 2023
b. Time-series analyses for individual lake studies should have been generated, where lakes are selected based on scientific or societal relevancy

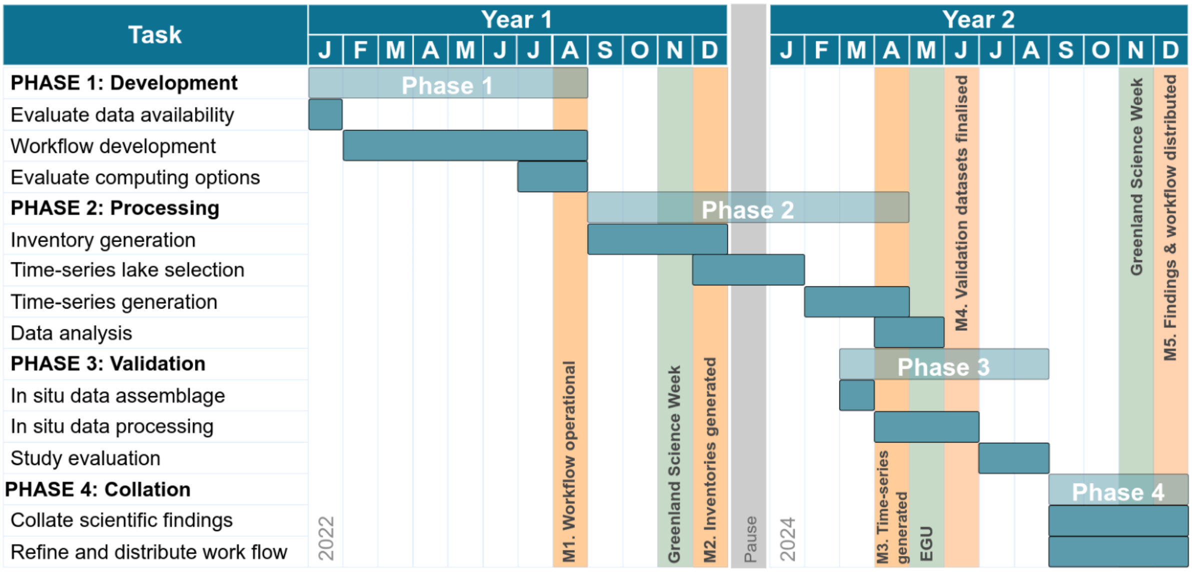

Figure 1. GrIML proposed project timeline. Note that due to parental leave, the project is offset by one year exactly as denoted by the pause between Year 1 and Year 2 (i.e. end of Year 1 is January 2024 and the end of Year 2 is January 2025).

Figure 1 highlights five milestones (M1-5) associated with GrIML's two objectives:

i. Finalisation of the workflow for operational use
ii. The generation of the Greenland-wide inventories of ice-marginal lakes
iii. The generation of the time-series record for selected ice-marginal lakes
iv. Finalisation of the in situ datasets, to be used as validation against the inventories and time-series
v. Submission of the scientific publication detailing the findings, and distribution of the workflow

The following sections will outline how these milestones have been achieved, and how the two objectives of the GrIML project have been addressed.

3 WORK PERFORMED

3.1 Scientific context

The Greenland Ice Sheet and surrounding peripheral glaciers and ice caps (PGICs) are predicted to be the largest cryospheric contributors to sea level rise over the next century (AMAP, 2021). Projections often assume meltwater flows directly into the ocean, yet an increasing portion is temporarily stored in ice-marginal lakes at glacier termini (Shugar et al., 2020). These lakes, formed when meltwater becomes trapped at glacier edges, represent a dynamic and significant component of terrestrial water storage (Sutherland et al., 2020). While some lakes are stable, many are highly dynamic and prone to sudden drainage events, known as GLOFs (Glacial Lake Outburst Floods), which resemble megafloods. GLOFs in Greenland can cause glacier speed-ups (Kjeldsen et al., 2017), alter downstream erosion and sedimentation (Grinsted et al., 2017), and impact water salinity (Kjeldsen et al., 2014).

The presence of ice-marginal lakes introduces thermo-mechanical processes, including lacustrine melting and calving, that enhance ice mass loss and alter glacier dynamics (Sutherland et al., 2020). These processes are well-documented at Russel Lake near Russel Glacier, West Greenland, where lake presence accelerates melt and undercutting (Carrivick et al., 2017; Dømgaard et al., 2024). With continued climate warming, ice-marginal lakes are expected to become more numerous, larger, and warmer, likely increasing melt rates and GLOF frequency (Carrivick and Tweed, 2016; Shugar et al., 2020). Despite their growing significance, ice-marginal lakes remain largely absent from sea level projections, which typically assume direct meltwater runoff, overlooking their intermediary storage role and changing dynamics as glaciers retreat onto land.

Mapping ice-marginal lakes is challenging due to their highly variable characteristics. Remote sensing methods, such as multi-spectral and SAR imagery combined with DEM analyses, have been effective in mapping these lakes across regions like Greenland, Alaska, and High Mountain Asia (How et al., 2021; Chen et al., 2021). However, the diversity in lake conditions—such as sediment loads, snow, and ice cover—requires multi-method classification approaches (How et al., 2021). Most existing lake inventories are static, failing to capture the dynamic nature of ice-marginal lakes or changes over time. Given the expected growth and evolution of these lakes, creating a time-series inventory is crucial for assessing their impact on sea level projections (Shugar et al., 2020; Zhang et al., 2024).

3.2 Methods

3.2.1 Ice marginal lake classification

Water bodies are classified using three complementary approaches to capture a broad range of water body characteristics that encompass the variability in ice marginal lake conditions.

1. SAR Backscatter Classification (SAR): Sentinel-1 GRD scenes (dual-polarization C-band) are processed to generate calibrated, ortho-corrected data (see Section 3.3, Table 1 for data description). Pre-processing steps include thermal noise removal, radiometric calibration, and terrain correction using SRTM 30 or ASTER DEM. Summer acquisitions (1 July–31 August) between 2016 and 2023 are filtered to HH polarization and averaged into 10 m resolution mosaics for each year. These mosaics are smoothed (50 m median filter) and classified using a static threshold optimized for detecting open water (How et al., 2021).

2. Multi-Spectral Indices Classification (VIS): Sentinel-2 MSI TOA Level-1C scenes (Section 3.3, Table 1) are used with cloud masks to exclude opaque and cirrus clouds. Key bands (blue, green, red, NIR, and SWIR) are resampled to 10 m

resolution and averaged into summer mosaics. Five spectral indices—NDWI, MNDWI, AWEI (shadow/no shadow), and BRIGHTNESS—are applied to detect water bodies, targeting features like shadow, snow/ice, sediment, and snow-covered areas. Thresholds are based on prior studies of ice-marginal lakes (How et al., 2021; Shugar et al., 2020), requiring positive classifications across all indices.

3. DEM-Based Sink Detection (DEM): ArcticDEM 2-metre mosaics (Section 3.3, Table 1) are smoothed (110 m median filter), and depressions are identified by subtracting filled DEMs (over a 50-pixel window) from the original surface, delineating lake outlines. As this method indirectly infers water presence, validation is required to confirm classifications.

Identified water bodies are compiled for each inventory year and filtered via three steps: 1) by location; 2) by size; 3) by manual curation. Firstly, lakes are filtered based on their location relative to the ice margin. Here, a 1 km buffer is derived around the MEaSUREs GIMP 15 m ice mask and classified water bodies are retained if they are located within the buffer (Howat, 2017; Howat et al., 2014). Classified water bodies are filtered by size, only retaining lakes above a minimum size threshold of 0.05 km^2; as adopted by How et al. (2021).

Finally, each inventory year dataset is manually curated to remove misclassifications, edit classifications (for example, where the shadowing mask does not adequately remove shadowing effects), remove detected water bodies that do not hold water in specific years, and remove water bodies that are detached from the ice margin. This manual curation is carried out via visual inspection of Sentinel-2 TOA Level-1C true colour composites from each inventory year.

The data production pipeline is deployable as a Python package called GrIML (How, 2024; How et al., In prep, a), which is accompanied by thorough documentation and guidelines on its use (at https://griml.readthedocs.io). This ensures a high level of reproducibility and transparency that adheres to the FAIR (Findability, Accessibility, Interoperability, and Reusability) principles (Wilkinson et al., 2016).

3.2.2 Surface lake temperature estimates

A summer surface water temperature estimate is provided with each classified lake across inventory years. Surface water temperature estimates are derived from all Landsat 8 and Landsat 9 OLI/TIRS surface temperature data acquired in the month of August for each inventory year. Averages are calculated from scene acquisitions in the month of August to limit the risk of mis-estimates due to ice-covered conditions. Surface temperature values (*LSTland*) are corrected to surface water temperature (*LSTwater*, degrees Celsius) using the following calibration (NASA Applied Remote Sensing Training (ARSET) program, 2022; Dyba et al., 2022):

$$LSTwater = (0.806 \times (LSTland \times 0.00341802 + 149.0) + 54.37) - 273.15$$

This calibration has previously shown strong correlations against in situ measurements (RMSE = 3.68°C and R^2 = 0.8) from 38 lakes in Poland, highlighting accurate estimates through a simple linear calibration (Dyba et al., 2022). Remotely sensed surface temperature estimates in Greenland are compared to six lake records from SW Greenland - Kangerluarsunnguup Tasia (64°07'50"N, 51°21'36"W) and Qassi-Sø (64°09'14"N, 51°18'27"W) (GEM BioBasis, 2024), Russell Lake (67°13'77"N, 50°07'63"W) (courtesy of Kristian K. Kjeldsen), and two lakes as part of the Asiaq Greenland Survey hydrological monitoring programme (Qamanersuaq, 62°91'32"N, 49°83'33"W; and ST924, 64°12'99"N, 51'36"39W) (measurements funded under the ESA Living Planet Fellowship fieldwork CCN).

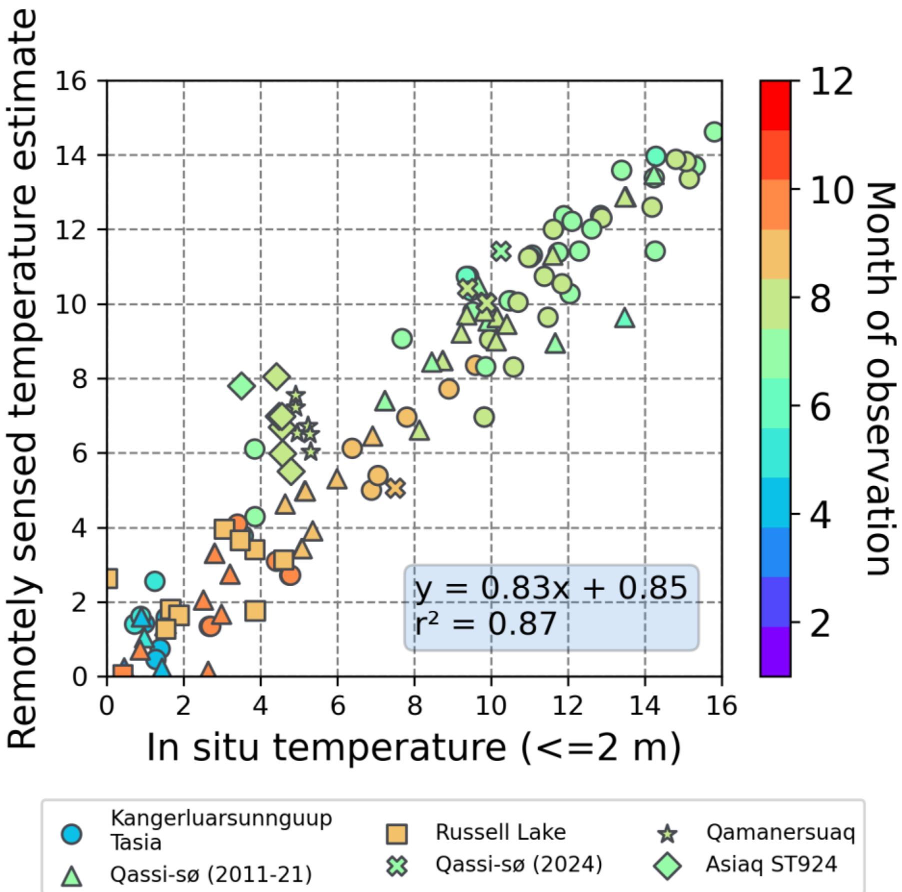

Figure 2: Comparison of in situ surface (2 m) water temperature measurements with remotely sensed temperature estimates from Kangerluarsunnguup Tasia, Qassi-Sø (from GEM BioBasis, 2024; and Asiaq Greenland Survey), Russell Lake (courtesy of Kristian K. Kjeldsen), and two other sites in SW Greenland (coordinated by Asiaq Greenland Survey, funded under the ESA Living Planet Fellowship fieldwork CCN). All sites demonstrate a relatively strong correlation, with values exhibiting a correlation (r-squared value) of 0.87. From How et al. (Submitted).

Comparison of in situ lake temperature measurements with those estimated using the remote sensing approach adopted here exhibit a strong correlation (r^2 = 0.87), with an

RMSE of 1.69 °C, suggesting that the remotely sensed temperature estimates are indicative of lake surface temperatures (Figure 2). An error estimation of ± 1.2 °C is determined, based on the average difference from data points across all lake sites.

3.3 Data

Table 1. Summary of satellite data sources

Satellite	Data product	Acquisition filters	Spatial resolution
Sentinel-1	Ground Range Detected (GRD) dual-polarization C-band SAR images	Interferometric Wide Swath (IW) Horizontal-Horizontal (HH) polarisation 01 Jul to 31 Aug	10 metres
Sentinel-2	Multispectral instrument (MSI), Top of Atmosphere (TOA), Level 1C images	01 Jul to 31 Aug 20% max. cloud cover	10 metres
-	ArcticDEM mosaic (version 3)	-	2 metres
Landsat 8/9	Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS), Collection 2, Level 2, surface temperature science product	01 to 31 Aug 30% max. cloud cover	30 metres

3.4 Results

3.4.1 The ice marginal lake inventory series, 2016-2023

The dataset catalogs 4,543 ice-marginal lakes, with 2,918 ±36% lakes automatically delineated as part of the inventory series (Figure 3) (How et al., 2025). Among these, 2,054 ± 36% are in contact with the ice sheet, while 864 ± 36% are associated with PGICs. The southwest (SW) region contains the greatest number of lakes compared to other regions, with 786 lakes automatically identified (640 at the ice sheet margin and 146 at PGIC margins). In contrast, the northern (NO) region features a notably high concentration of PGIC lakes, with 278 identified, compared to only 37 in the southeast (SE). This pattern is likely due to the higher density of PGICs in northern Greenland.

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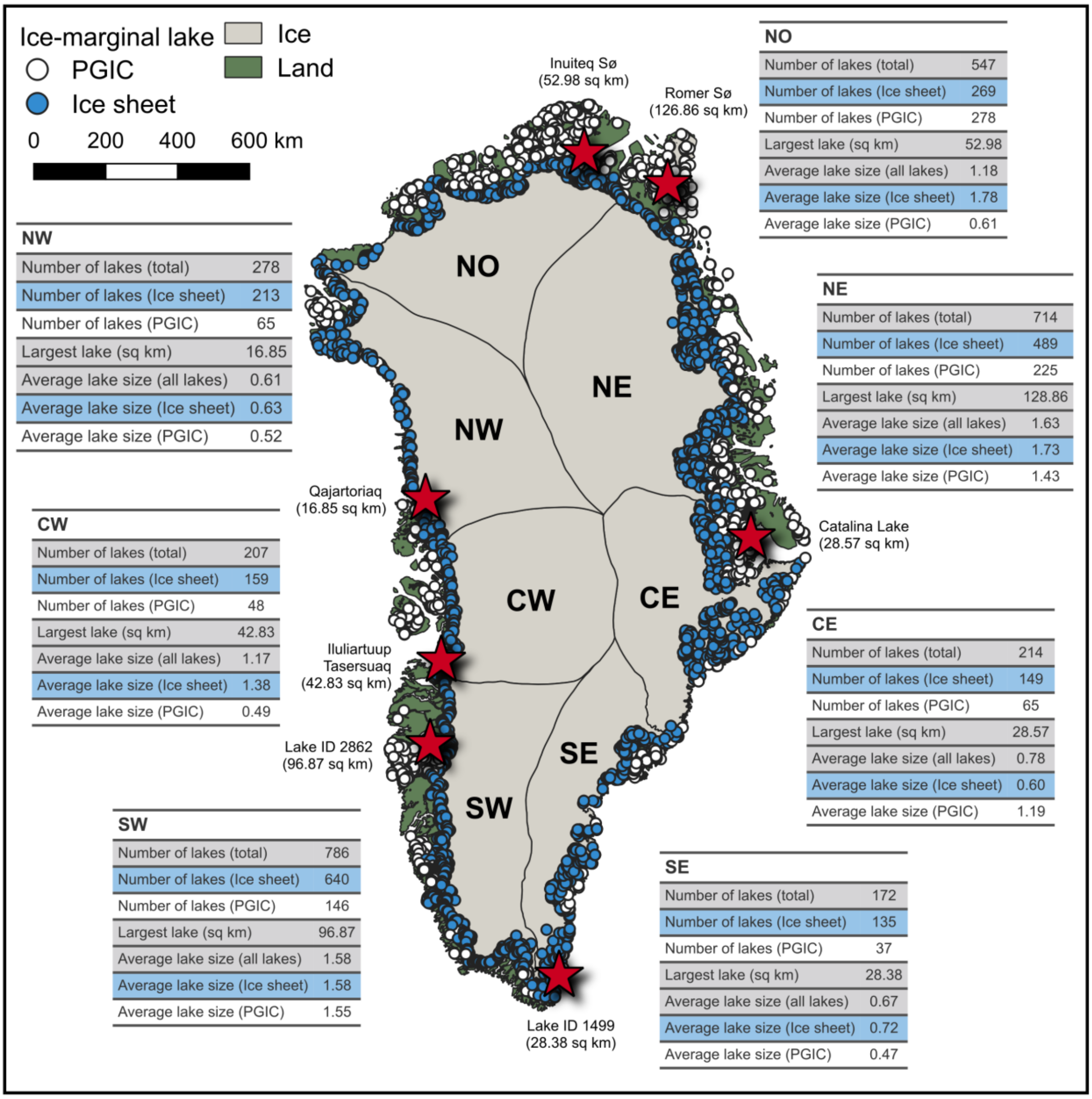

Figure 3. An overview of the abundance of lakes in ice-marginal lake inventory series, 2016-2023. Each mapped point denotes a unique lake, mapped across the Greenland Ice Sheet margin (blue) and the surrounding PGIC margins (white). Statistics are associated with each region, with red starred points on the map corresponding to the largest lake of each region. Placenames for the largest lakes are sourced from the placename database provided by Oqaasileriffik (the Language Secretariat of Greenland). The catchment regions are those defined by Mouginot and Rignot (2019). Base maps for plotting are from QGreenland v3.0 (Moon et al., 2023). From How et al. (Submitted).

Comparing annual ice-marginal lake inventories from 2016 to 2023 reveals minimal fluctuation in lake abundance (Figure 3 and 4). At the ice sheet margin, the number of lakes varies between 1808 (2018, 2023) and 1948 (2019), with the SW region showing the greatest variation, ranging from 547 (2018, 2023) to 590 lakes (2021). The CW and SE margins experience the smallest changes, fluctuating by just 13 and 14 lakes, respectively. These fluctuations show no clear spatial or temporal patterns (Figure 3 and 4).

For lakes at the margins of peripheral glaciers and ice caps (PGICs), abundance varies from 745 (2022) to 818 (2019), with smaller regional fluctuations compared to the ice sheet margin (Figure 3 and 4). On average, PGIC lakes fluctuate by 11 lakes, while ice sheet lakes vary by 26. The largest changes are in the NO and NE regions, fluctuating by 26 and 20 lakes, likely reflecting the higher number of lakes in these regions. Conversely, regions with fewer lakes (e.g., NW, SE, CE, and CW) show the smallest changes. Like the ice sheet margin, no distinct spatial or temporal trends are observed (Figure 4b).

The largest lake in the dataset is Romer Sø, situated in northeast Greenland, with an area of 126.86 km^2. The average lake size across the dataset is 1.29 km^2, while the median size is 0.27 km^2. Notably, 82% of the lakes (2,395) have sizes ranging between 0.05 and 1.00 km^2, and only 59 lakes (2%) are larger than 10 km^2.

The inventory also tracks lake area changes over time by comparing lake extents across each inventory year using the direct classification approaches (SAR and/or VIS) (Figure 4 and 5). Of the 918 lakes for which area changes can be monitored, 243 have increased in size by more than 0.05 km^2 between 2016 and 2023, 675 have shrunk by more than 0.05 km^2, and 778 have shown little to no change (area changes within ± 0.05 km^2). The most significant area changes generally occur in larger lakes, such as those in the northeast (Figure 5b) and southwest regions (Figure 5d).

Average lake area at the ice sheet margin remains relatively steady across the inventory years. The smallest change occurs in the SE region (0.09 km^2), while the largest is in the CE region (1.25 km^2) (Figure 4a). The NO region has the largest average lake size in 2019 (2.40 km^2), coinciding with the highest lake abundance (1,948), but no significant regional or temporal trends emerge.

Lakes adjacent to PGICs tend to have larger average areas (1.69 km^2) compared to ice sheet lakes (1.30 km^2). Fluctuations in average lake area are also greater for PGIC lakes, ranging from 0.16 km^2 (SE) to 5.67 km^2 (CE) (Figure 4b). The NE region shows a notable increase in average lake size to 5.88 km^2 in 2022, followed by a drop to 2.92 km^2 in 2023. However, there is no consistent relationship between lake abundance and changes in lake area across regions or years.

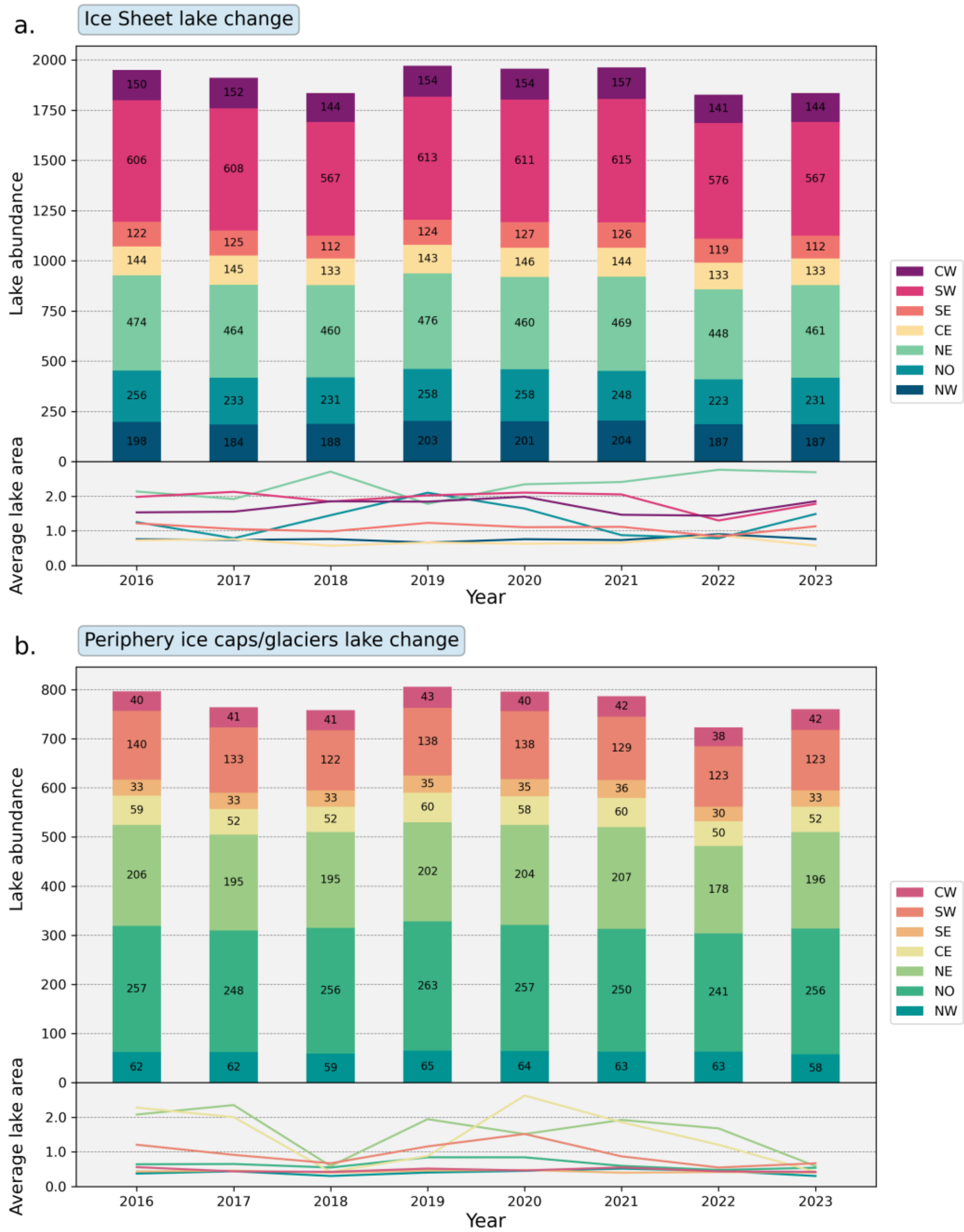

Figure 4. Change in the abundance and average area (km²) of ice marginal lakes around the ice sheet margin (a) and the surrounding ice caps and periphery glaciers (b). Each of the coloured bars denote lake abundance per region for a given year of the inventory series (2016-2023), with annotated numbers corresponding to the number of lakes classified for each region. Each line plot indicates the average lake area per region for a given year of the inventory series. Average lake area is compiled from all SAR and VIS classified lakes, as DEM classifications are not a direct detection of water bodies. From How et al. (Submitted).

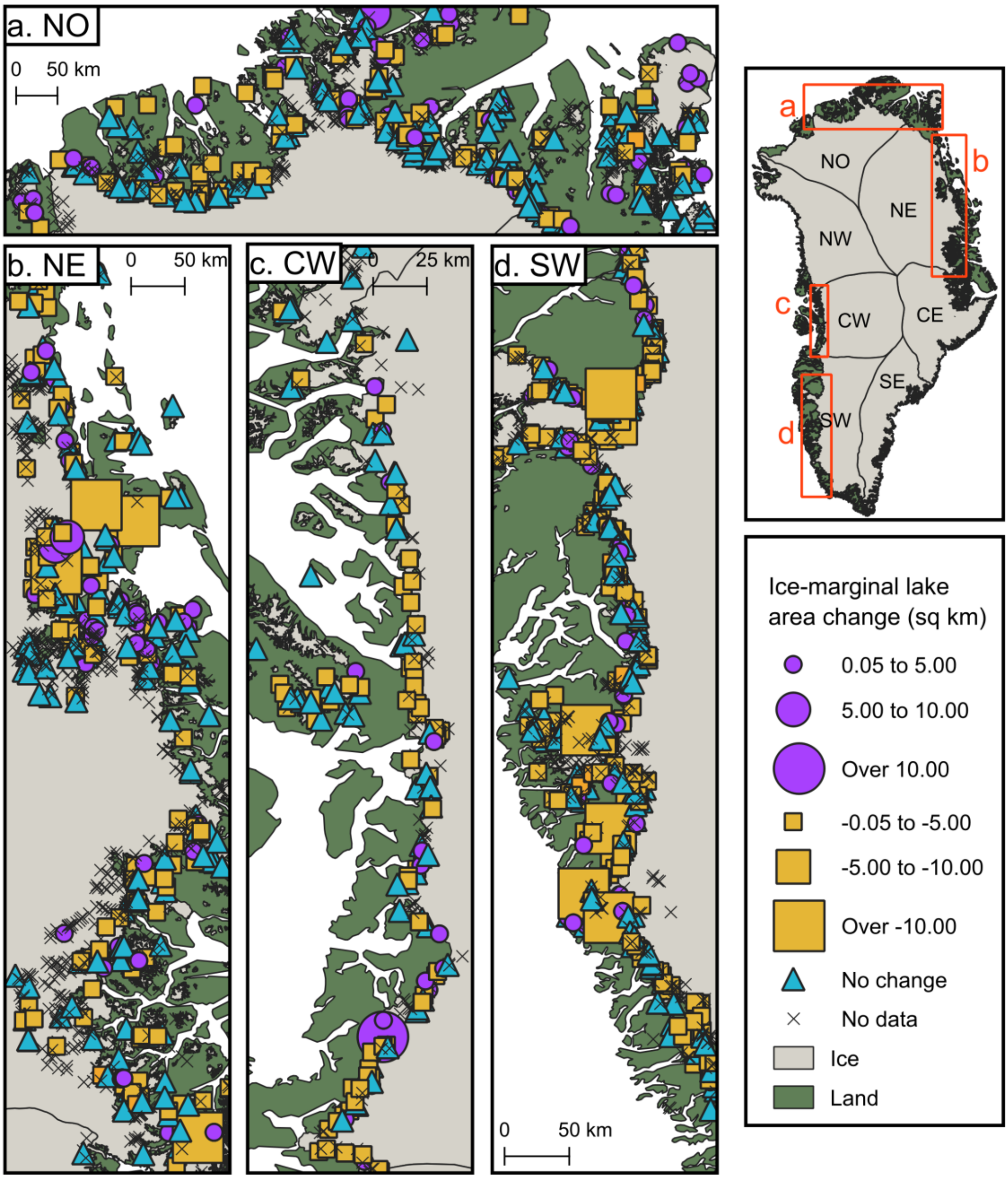

Figure 5. Change in lake area across the ice-marginal lake inventory series, 2016-2023. Example regions are highlighted from NO (a), NE (b), CW (c) and SW (d) regions of both the Ice Sheet and the PGICs. Lake area increase (purple circles), lake area decrease (yellow squares) and unchanged lake areas (blue triangles) are mapped, with the size of the symbol denoting the amplitude of change (km2). Each point denotes the change in lake size across the inventory series, as classified using the SAR and VIS methods. Lakes with no available area data (i.e. not classified using the SAR and VIS methods) are marked with crosshairs. From How et al. (Submitted).

3.4.2 Ice marginal lake temperature evolution

A slight increase in surface lake temperature is evident, with the average lake surface temperature increasing from 5.8 ± 1.2 °C in 2016 to 6.2 ± 1.2 °C in 2023 (Figure 6). Fluctuations year on year vary, with instances of lake temperature falling between annual time steps (e.g. falling from 5.2 ± 1.2 °C to 4.4 ± 1.2 °C from 2017 to 208), rising (e.g. from 5.6 ± 1.2 °C to 6.2 ± 1.2 °C from 2022 to 2023), and remaining consistent (e.g. 5.6 ± 1.2 °C from 2021 to 2022).

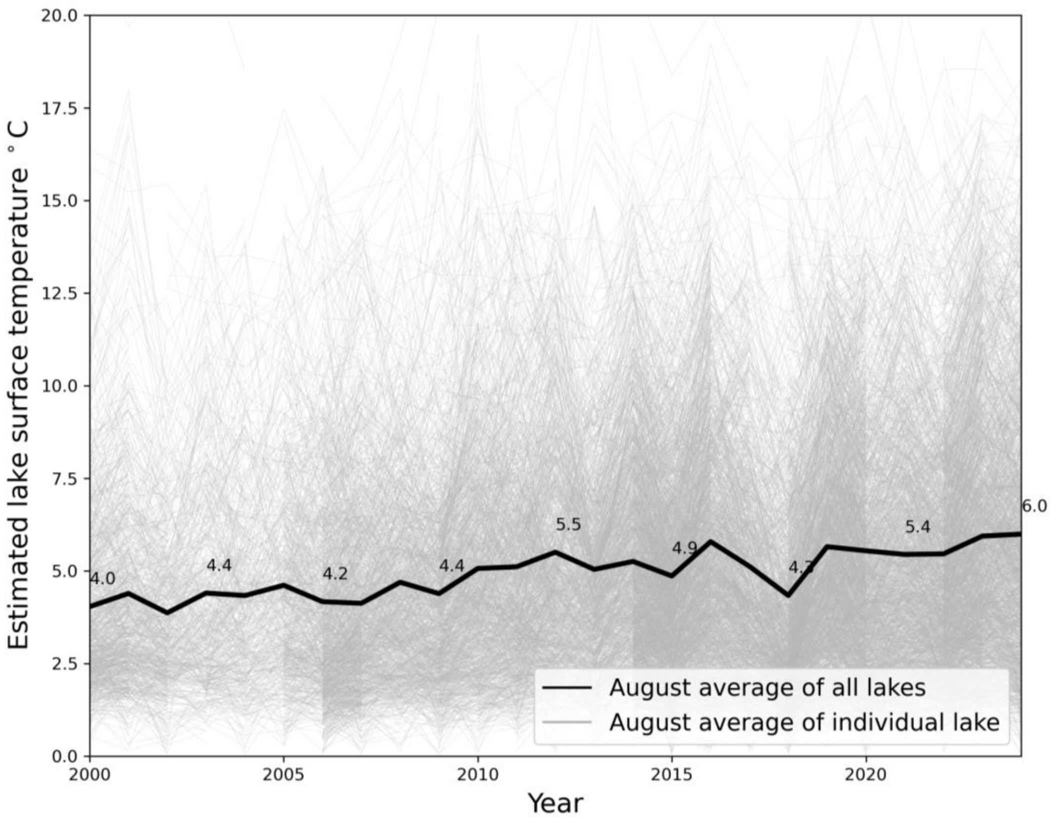

Figure 6. Average surface lake temperature estimates from the month of August at each inventory lake for each inventory year (2016-2023) (grey), with the average of all lakes overlaid (black). From How et al. (In prep, b).

The record of ice marginal lake surface temperature can be extended back in time to the beginning of the Landsat thermal/infrared imaging era to form a multi-decadal time-series of lake temperature evolution. Since 1985, warming has occurred on average at all ice marginal lakes. A marked warming of 3.8 ± 1.2 °C is evident at small lakes with a surface extent between 0.05 km² and 0.2 km² (Figure 7; top panel). Warming is also evident at larger lakes (<= 150 km²), increasing from 2.5 to 4.3 ± 1.2 °C .

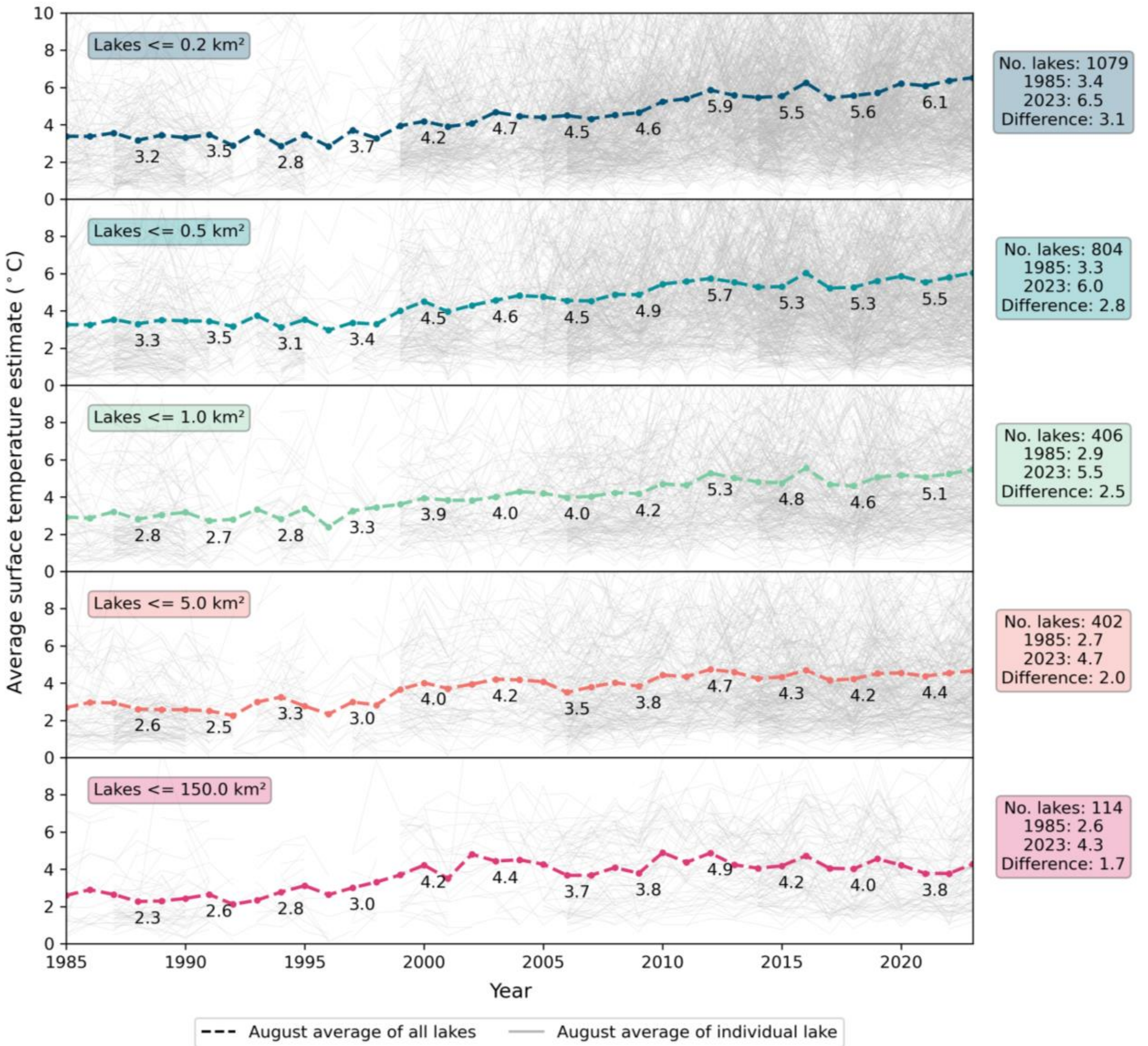

Figure 7. Average surface lake temperature estimates from the month of August at each inventory lake for the Landsat 4-9 era (1985-2023). Lakes are divided by size, with the smallest lake group (<= 0.2 km²) represented in the top plot and the largest lake group (<= 150 km²) in the bottom plot. August averages for each lake are plotted in grey, with the average of each lake group overlaid in the coloured dashed line. From How et al. (In prep, b).

3.4.3 Time-series analysis #1: Nordbosø and lakes in the catchment of Eqalorutsit Kangilliit Sermiat, South Greenland

Ice-marginal lakes around Eqalorutsit Kangilliit Sermiat, near Narsarsuaq, are being studied to determine whether meltwater discharge originates from basal melt or lake drainage. Fieldwork in early 2023 detected potential submarine basal melt at the glacier terminus (Hansen et al., Accepted). Five lakes, mapped previously in 2017 (How et al., 2021), were monitored between January and April 2023, coinciding with the collected field measurements (Figure 8a).

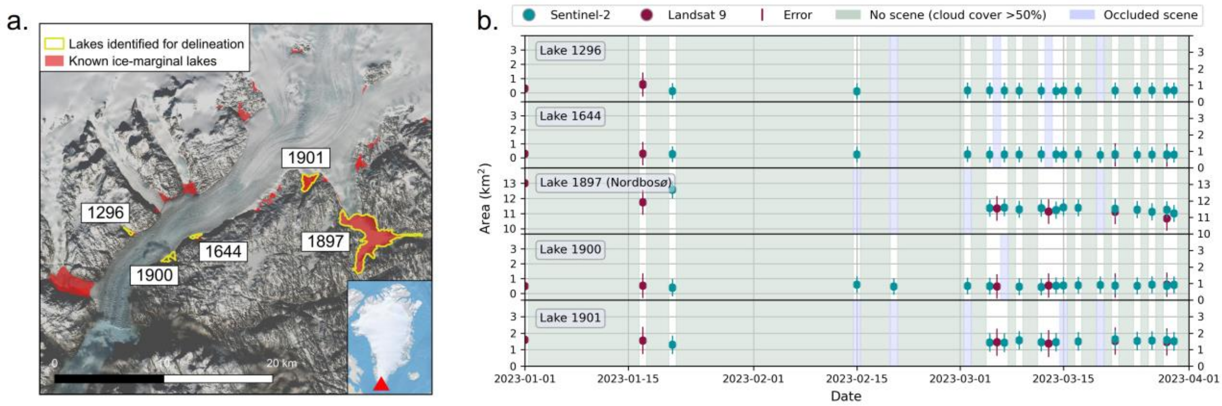

Figure 8. The five ice marginal lakes identified between January and April 2023 within the Eqalorutsit Kangilliit Sermiat catchment area. Known ice marginal lakes are identified from the 2017 inventory of Greenland ice marginal lakes (How et al., 2021) (a). The time-series of lake area change map surface extent from Sentinel-2 and Landsat 9 imagery (b). From Hansen et al. (In Press).

Time-series analysis of surface area across 21 images (17 Sentinel-2 and 6 Landsat 9 scenes) indicated limited variability in lake areas during this period, with the largest changes occurring early in the year, likely due to snow cover (Figure 8b). Later records showed reduced variability and higher data coverage. Error estimates for lake delineations were ± 4.45% (Sentinel-2) and ± 6.31% (Landsat 9). These findings suggest stable lake conditions without major drainage events during the observation period (Hansen et al., In Press).

3.4.4 Time series analysis #2: Hagen Bræ, North Greenland

An ice-marginal lake on Hagen Bræ exhibits periodic GLOF drainage cycles that may influence the glacier's surge-type behavior (Figure 9). Located ~60 km upstream of the terminus, this 25.81 sq km lake stores significant meltwater compared to nearby seasonal supraglacial lakes. Historical records reveal drainage events approximately every three years (Table 2), with the most recent in 2021 coinciding with a sharp ice velocity slowdown (Solgaard et al., 2020), suggesting a link between GLOFs and glacier dynamics.

ICESat-2 data shows lake surface heights ranging from 400–550 m (above WGS84), with a major drainage event in 2019 causing a drop of 80–100 m. Future work aims to estimate the volume of this event to better quantify subglacial meltwater storage and its role in the hydrology of Hagen Bræ.

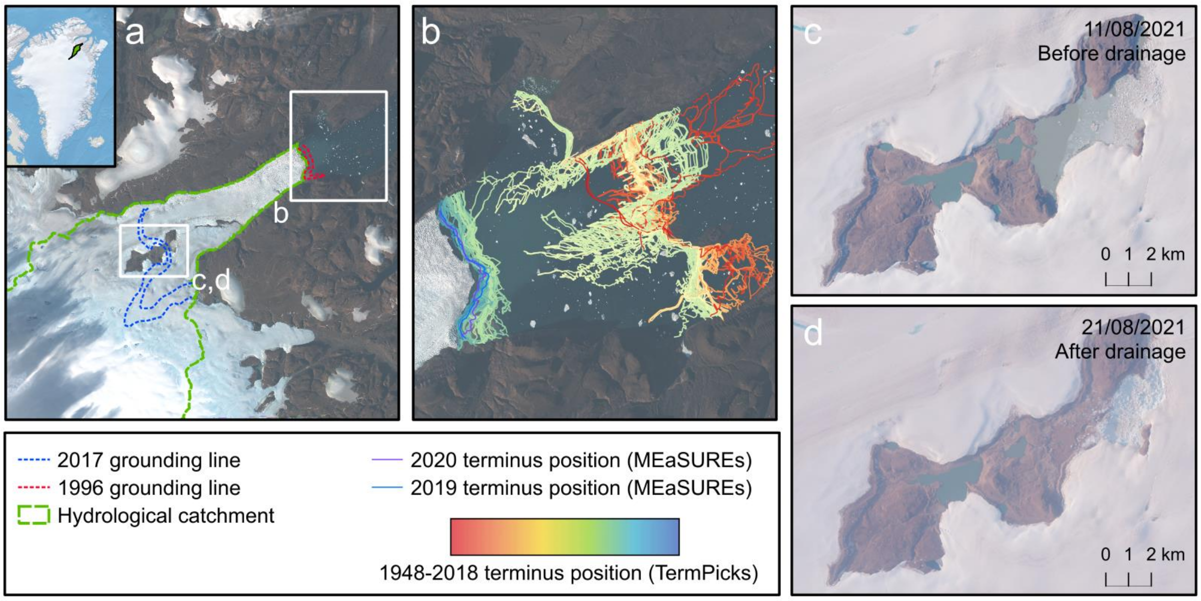

Figure 9: An overview of the Hagen Bræ glacier outlet from a Sentinel-2 visible composite image (captured 31/08/2023), with InSAR-derived grounding line positions from 1996 and 2017 (ESA CCI+ dataset) and hydrological catchment (modified to correspond with the terminus position at the time of Sentinel-2 composite acquisition; Mankoff et al., 2021) (a). Record of terminus positions compiled from TermPick (Goliber et al., 2023) and MEASUREs (Howat et al., 2014; Howat, 2017) datasets, shows the retreat of the terminus from 1948-2020 (b). Sentinel-2 visible composite images from August 2021 show a substantial GLOF event from a lake sharing a margin with a nunatak ~60 km upstream of the glacier terminus (c, d). Note the lake is the largest water body depicted, with the other surrounding water bodies hydrologically connected to varying degrees. From How et al. (In prep, c).

Table 2. Drainage events identified at the Hagen Bræ nunatak lake

Drainage period	Platform identified from
03 - 12/09/1988	Landsat 5
29/08 - 07/09/1992*	Landsat 5
12 - 19/04/1998	Landsat 5
25/07/2001 - 29/05/2002*	Landsat 7/ASTER
27/07/2004 - 03/06/2005*	Landsat 7/ASTER
23 - 30/07/2008	Landsat 7
28/08/2011 - 14/06/2012*	ASTER/Landsat 7
24/09/2014 - 16/03/2015*	Landsat 8/9
17 - 25/08/2018	Sentinel-2
11 - 17/08/2021	Sentinel-2

**Drainage period is affected greatly by scene availability and therefore does not accurately reflect the actual duration of drainage*

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The GrIML project has successfully achieved its two primary objectives, delivering a comprehensive ice-marginal lake inventory series for the Sentinel era (2016–2023) and developing individual lake time-series analyses to explore their impact in different settings (How et al., 2025). These outputs represent a significant step forward in understanding Greenland's terrestrial water storage and its role in glacier dynamics and future sea level projections.

The ice-marginal lake inventory series demonstrates a robust methodology combining multi-sensor remote sensing techniques to track lake abundance, distribution, and dynamics. While the total number of lakes and their average sizes remain relatively stable over the time series, localized variations in lake area and abundance highlight the dynamic nature of these systems. Furthermore, the inclusion of surface temperature estimates adds a novel dimension to the dataset, revealing a long-term warming trend consistent with regional climate change.

The time-series analyses emphasize the role of ice-marginal lakes in influencing ice dynamics, with evidence of significant interactions at key sites in SW and NE Greenland. These findings enhance our understanding of meltwater storage dynamics, offering insights into processes such as calving and lacustrine-driven melting. By capturing both spatial and temporal trends, the GrIML dataset addresses a critical gap in the modelling of Greenland's hydrological system.

Ultimately, the outcomes of this project reinforce the importance of incorporating ice-marginal lakes into sea level rise projections, hydropower planning, and ecological studies. The openly accessible datasets and workflows developed ensure a high degree of transparency and reproducibility, fostering further research and application in these areas. It is intended to continue the ice-marginal lake inventory series, with updates every year to the dataset hosted on the GEUS Dataverse (How et al., 2025).

4.2 Recommendations

1. **Integration into Sea Level Rise Models**
   The findings of this project underline the need for global sea level rise models to incorporate ice-marginal lake dynamics as an intermediary stage of meltwater storage. This will improve the accuracy of projections by addressing the delays and impacts of meltwater storage and drainage.

2. **Enhanced Monitoring Systems**
   While the current inventory provides a robust baseline, future efforts should focus on integrating additional data sources, such as higher-resolution satellite imagery and emerging remote sensing technologies (e.g., hyperspectral sensors), to improve the classification of challenging conditions such as ice-covered lakes.

3. **Climate Change Projections and Scenario Analysis**
   With warming trends evident in lake surface temperatures, continued monitoring is critical to assess their future evolution under different climate scenarios. This could involve extending the dataset both spatially (e.g., to include other Arctic regions) and temporally (e.g., further back into the Landsat archive).

4. **Societal Applications and Stakeholder Engagement**
   The openly accessible GrIML datasets should be actively disseminated to stakeholders, including hydropower developers, local communities, and ecological researchers. Collaborative efforts should aim to translate these findings into actionable strategies for relevant applications, such as optimizing hydropower infrastructure.

5. **Further Incorporation of In Situ Observations**
   To validate and refine remote sensing datasets, greater emphasis should be placed on collecting in situ observations of ice-marginal lake characteristics, such as depth, volume, and temperature profiles, particularly in regions with high societal relevance.

6. **Expansion of Reproducible Workflows**
   The development of the GrIML Python package represents a major advancement in transparent data production. Continued refinement of this tool, along with expanded training and user support, will enable broader adoption by the scientific community and ensure the sustainability of this research effort.

By addressing these recommendations, the GrIML project can continue to support critical advances in understanding the role of ice-marginal lakes in Greenland's hydrological and glaciological systems, while facilitating further applications of this knowledge to societal and environmental challenges.

4.3 Roadmap for future work

a. Annual Updates to the Ice-Marginal Lake Inventory Series
Building on the existing inventory, future work should focus on adding new years as satellite imagery becomes available. This year-on-year expansion will create a longer-term dataset, enabling improved trend analyses of ice-marginal lake dynamics.

b. Extension of the Lake Temperature Record
To deepen insights into the relationship between lake temperatures and regional climate, the surface temperature record should be extended back to the beginning of the Landsat era. This would provide a multi-decadal perspective on warming lake trends. Figure 7 already demonstrates preliminary efforts into this, highlighting a clear and marked warming trend in ice-marginal lake surface temperatures.

c. Improved Validation of Lake Temperatures
Validation of the temperature estimates should be prioritized through the integration of in situ monitoring data. In situ monitoring data could be collected in collaboration

with pre-existing monitoring programs, such as the hydrological station maintained by Asiaq Greenland Survey. Future efforts could expand this existing monitoring network, thereby continuing to root field efforts in Greenland with Greenlandic research institutions.

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6 PUBLICATIONS

6.1 Research publications

6.1.1 Published

Carrivick, J.L., **How, P.**, Sutherland, J., Cornford, S., Lea, J., Tweed, F., Grimes, M., and Mallalieu, J. (2022) Ice-marginal proglacial lakes across Greenland: present

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Dømgaard, M., Kjeldsen, K.K., **How, P.** and Bjørk, A. (2024) Altimetry-based ice-marginal lake water level changes in Greenland. Comm. Earth Environ. 5, 365, https://doi.org/10.1038/s43247-024-01522-4

Goldstein, S.N., Ryan, J.C., **How, P.**, Esenther, S.E., Pitcher, L.H., Lewinter, A.L., Overstreet, B., Kyzviat, E.D., Fayne, J., Smith, L.C. (2023) Proglacial river stage derived from georectified time-lapse camera images, Inglefield Land, Northwest Greenland. Front. Earth Sci. 11:960363. https://doi.org/10.3389/feart.2023.960363

Karlsson, N. B., Mankoff, K. D., Solgaard, A. M., Larsen, S. H., **How, P.**, Fausto, R. S., & Sørensen, L. S. (2023). A data set of monthly freshwater fluxes from the Greenland ice sheet's marine-terminating glaciers on a glacier–basin scale 2010–2020. GEUS Bulletin, 53. https://doi.org/10.34194/geusb.v53.8338

Hansen, K., Karlsson, N. B., **How, P.**, Poulsen, E., Mortensen, J. and Rysgaard, S. (In Press) Unique in-situ measurements from Greenland fjord show winter freshening by subglacial melt. Nat. Geosci.

How, P., Petersen, D., Karlsson, N.B., Kjeldsen, K.K., Raundrup, K., Messerli, A., Rutishauser, A., Carrivick, J.L., Lea, J.M., Fausto, R.S., Ahlstrøm, A.P., Andersen, S.B. (2025) Greenland ice-marginal lake inventory annual time-series Edition 1. GEUS Dataverse. https://doi.org/10.22008/FK2/MBKW9N

Messerli, A., Arthur, J., Langley, K., **How, P.** and Abermann, J. (2022) Snow cover evolution at Qasigiannguit Glacier, southwest Greenland: a comparison of time-lapse imagery and mass balance data. Front. Earth Sci. 10, 970026. https://doi.org/10.3389/feart.2022.970026

6.1.2 In preparation/Submitted

How, P. et al. (Submitted) The Greenland Ice Marginal Lake Inventory Series from 2016 to 2023. Earth System Science Data (ESSD).

How, P. (In prep, a) GrIML: A Python package for investigating Greenland's ice marginal lakes under a changing climate.

How, P. et al. (In prep, b) An 8-year record of Greenland-wide ice marginal lake change

How, P. et al. (In prep, c) Hydrological influence of ice marginal lake drainage on surge-type dynamics of a marine-terminating glacier in NE Greenland.

6.2 Software/code publications

Goldstein, S.N. and **How, P.** (2022) sethnavon/PyTrx_Minturn_Elv: Minturn River Stage Data (minturn_elv1.1). Zenodo. https://doi.org/10.5281/zenodo.6560889

How, P. (2022a) PennyHow/GrIML: GrIML v0.0.1. Zenodo. https://doi.org/10.5281/zenodo.6498007

How, P. (2022b) PennyHow/PyTrx: PyTrx v1.2.4. Zenodo. https://doi.org/10.5281/zenodo.6624346

How, P. (2024) PennyHow/GrIML: GrIML v0.0.2. Zenodo. https://doi.org/10.5281/zenodo.11395471

6.3 Conference/invited talks and posters

“Investigating Greenland’s ice-marginal lakes under a changing climate, 2016-2023", poster presented at European Polar Science Week 2024, Copenhagen, Denmark (September 2024)

“Investigating Greenland’s Ice Marginal Lakes in a Changing Climate”, talk presented at GLIMPSE seminar, Copenhagen, Denmark (March 2024).

“Recent advances in monitoring the Greenland Ice Sheet”, talk presented at Greenland Science Week 2023 conference, Nuuk, Greenland (November 2023).

“An inventory of ice-marginal lake across Greenland”, poster presented at the Mapping The Arctic 2023 conference, Nuuk, Greenland (May 2023).

“Ice marginal lakes in Greenland”, guest lecture presented at DTU Space, Denmark (July 2022).

“Ice marginal lakes in Greenland”, guest lecture presented at the ETH Zurich VAW (Laboratory of Hydraulics, Hydrology and Glaciology) group’s Glaciological Seminar (May 2022).

“Investigating Greenland’s ice marginal lakes under a changing climate (GrIML)”, talk presented to the GEUS board of directors under the Glaciology and Climate department’s ongoing activities (March 2022).