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MID-TERM REPORT

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

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1 EXECUTIVE SUMMARY

This mid-term report signifies the midway point of the GrIML project, where two clear sets of work have been identified and developed:

1. The identification of ice marginal lakes across Greenland to form a series of Greenland-wide inventories
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

The Greenland-wide inventories workflow has been developed, with testing applied to the 2017 inventory. Results suggest that the workflow confidently identifies and maps ice marginal lakes across Greenland when compared to the existing ESA CCI 2017 ice marginal lake inventory (How et al., 2021).

Ice marginal lake time-series analyses has been focused on two case studies thus far. The first of these is based around the Narsarsuaq area in South Greenland, with ice marginal lakes around Eqalorutsit Kangilliit Sermia classified to form a time-series as part of a larger project examining winter subglacial melt production (Karlsson et al., In prep). The second case study investigates an ice marginal lake at Hagen Bræ in North Greenland, where GLOF events may play an important role in the glacier's hydrology and surge-type dynamics.

2 OBJECTIVES AND WORKPLAN

By the end of Year 1 in GrIML (Fig. 1), the following objectives should be completed:

a. An operational workflow for deriving ice marginal lakes across Greenland should have been developed
b. A 2017 test inventory of ice marginal lakes should have been generated, with comparison to the pre-existing ESA CCI Glaciers (option 6) inventory from the same time period
c. Ice marginal lake inventories for the other monitoring years should have been generated, or at least a plan for their generation should have been developed
d. Individual lake studies for the time-series analysis should have been identified

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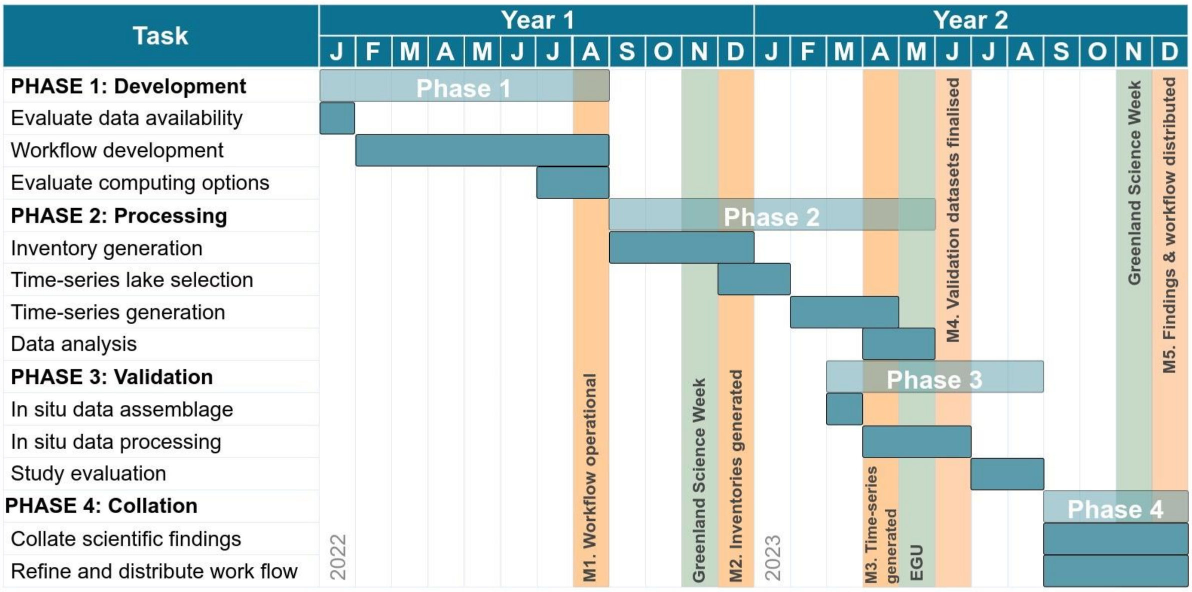

Figure 1. GrIML proposed project timeline. At the time of this bi-monthly report, we are nearing the end of Year 1 at the end of December 2023. Note that due to parental leave, the project is offset by one year exactly (i.e. end of Year 1 is January 2024, not January 2023; and the end of Year 2 is January 2025, not January 2024).

3 WORK PERFORMED

3.1 Scientific context

The work reported here can be split into two aims, summarized in the following scientific questions:

1. To map and monitor the distribution and size of ice marginal lakes in Greenland through time
    a. How are ice marginal lakes distributed across Greenland?
    b. How does the frequency and size of ice marginal lakes change over time under a changing climate?
2. To examine the influence of ice marginal lakes across different settings in Greenland that are scientifically and societally relevant
    a. Do ice marginal lakes make a significant contribution to subglacial water presence?
    b. How do GLOF events at ice marginal lakes have a lasting impact on ice dynamics? And how do GLOF events influence glacial settings over time?
    c. Do ice marginal lakes societally benefit or disadvantage the residing communities and associated activities?

The first of these aims will be addressed with the formulation of a series of ice marginal lake inventories, generated using a multi-classification remote sensing workflow (outlined in Section 3.2). The second of these aims will be addressed by examining

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individual ice marginal lakes that are scientifically and societally relevant, with this report showcasing two of the case studies being explored presently.

3.1.1 Methods

Ice marginal lakes are automatically classified using the GrIML workflow, which has been developed in the first half of the GrIML project (Fig. 2). This workflow is largely based on the workflow used to produce the ESA CCI 2017 ice marginal lake inventory (How et al., 2017), with modifications made to increase efficiency and unify the different methodologies. Water body classification is conducted via three independent methods for identifying ice marginal lakes from Synthetic Aperture Radar (SAR) and visible imagery (namely Sentinel-1 and Sentinel-2), and Digital Elevation Model (DEM) datasets. The GrIML workflow is available as a Python package, with all contents and documentation openly available through its GitHub repository (How et al., 2022a).

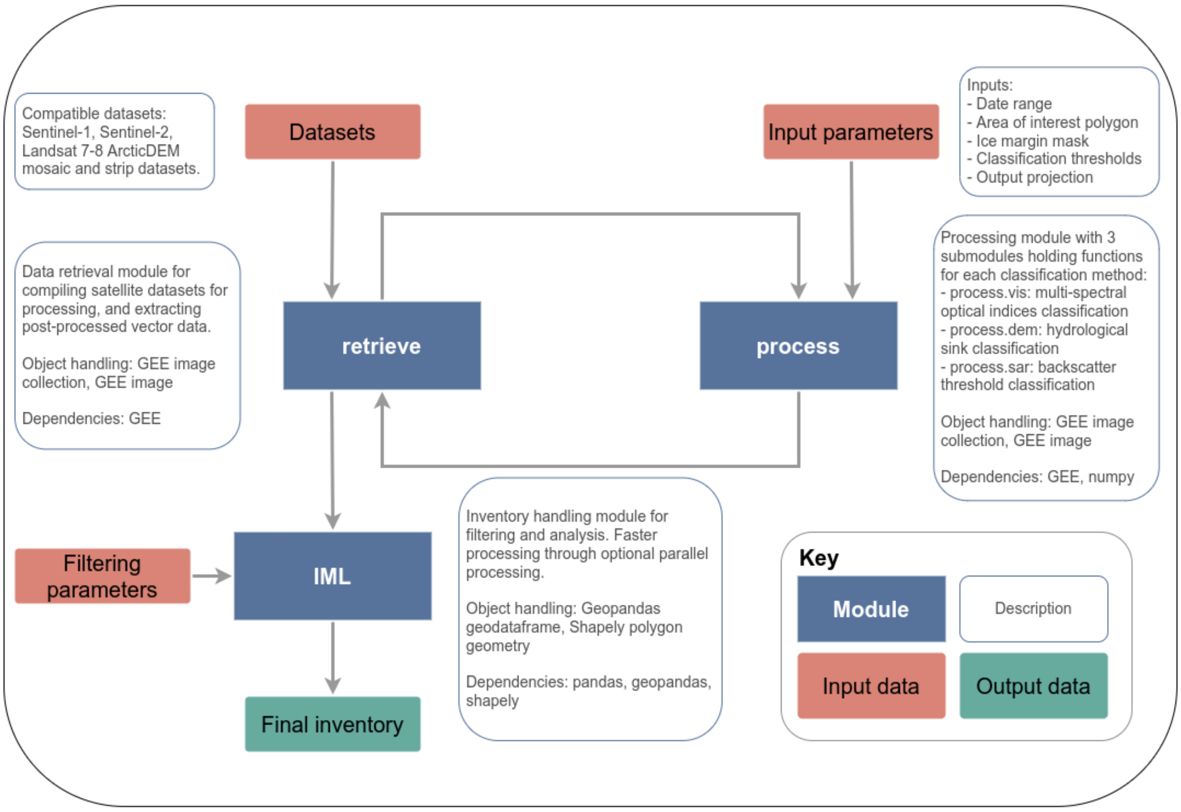

Figure 2: The GrIML workflow for classifying and filtering ice marginal lakes from SAR and visible remote sensing imagery, and DEM datasets (How et al., 2022a).

Instances where the GrIML workflow cannot be used for automated classification include the classification of ice-covered water, iceberg presence, and high snow coverage. In these cases, the areal extent of the water bodies are delineated manually using the GEEDiT (Google Earth Engine Digitisation Tool) toolbox (Lea, 2018; Goliber et al., 2022).

It was proposed that terrestrial time-lapse images would form one of the approaches for validating the GrIML workflow, and could also be used as supplementary information to one (or many) of the individual ice marginal lake studies. Within the first year of GrIML, updates and modifications have been made to the PyTrx toolbox for classifying glacial features and water bodies from terrestrial time-lapse images (Goldstein et al., 2023; How et al., 2022b; Messerli et al., 2022). Ice marginal lakes with opportunities to use and process terrestrial time-lapse imagery will be identified in the next phase of the GrIML project.

3.1.2 Data

Various datasets can be incorporated with the GrIML workflow for multi-sensor classification of ice marginal lakes from remotely sensed imagery and data products. These datasets are summarised in Table I.

Table I. Current satellite sensors/products incorporated into the GrIML workflow

Satellite sensor/product	Classification method	Active years	Spatial resolution
Sentinel-1	SAR (Synthetic Aperture Radar) backscatter thresholding	2014-present	10 m
Sentinel-2	Multi-spectral optical indices thresholding	2015-present	10 m
Landsat 7-9	Multi-spectral optical indices thresholding	2013-present	30 m
ArcticDEM mosaic	Hydrological sink analysis	N/A*	2 m

* The ArcticDEM mosaic is a product derived from optical stereo imagery spanning acquisitions between 2009 to 2017 (Porter et al., 2018).

3.2 Greenland-wide ice marginal lake inventories

The GrIML 2017 ice marginal lake inventory consists of 4097 unique lakes, covering the seven drainage basins of the Ice Sheet, and the surrounding ice caps (Fig. 3). All lakes detected are above the minimum area threshold of 0.05 km². The largest lake detected is 119.3 km² , which is the lake named Romer Sø that is present in front of the terminus of Elephant Foot Glacier (Northwest Greenland).

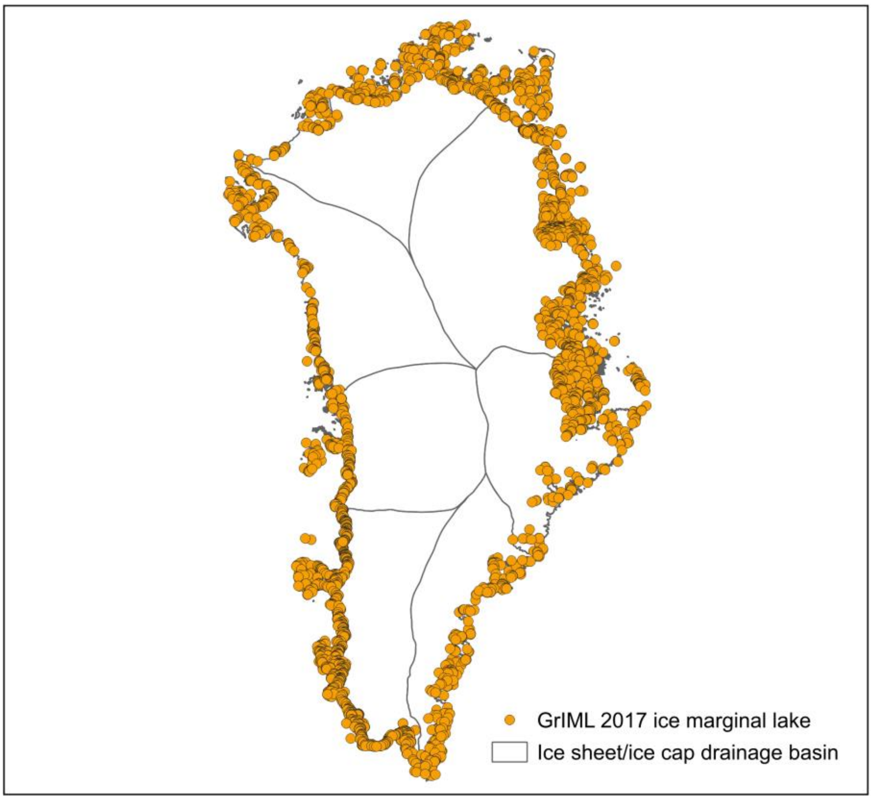

Figure 3: The GrIML 2017 ice marginal lake inventory, where each point (orange) represents the centroid of a unique lake classified with either the backscatter thresholding, multi-

spectral classification, or the DEM sink detection method; or a combination of these methods. The ice sheet/ice cap drainage basin outlines are taken from Mouginot and Rignot (2019).

In total, the three classification methods applied here culminated in 5818 lake polygons. 2877 lakes were detected using the DEM sink detection method on the ArcticDEM mosaic, 1587 lakes using the Sentinel-2 multi-spectral classification method, and 1354 lakes using the Sentinel-1 backscatter thresholding classification method.

As expected, the northern sectors of the Ice Sheet (i.e. northwest, NW; north, NO; and northeast, NE) held the greatest difficulties for classifying lakes due to persistent ice and snow cover, obscure shadowing and limited scene availability. As a result, many misclassifications had to be removed from these sectors. Icebergs obscure and occlude the periphery of lakes in some instances, even obscuring the entire lake periphery altogether such as in the case of Lake Hullet in SW Greenland which was not classified using any of the automated classification techniques. As a result, further manual work is needed to ensure that such lakes are included in the inventory.

A tentative comparison to the 2017 ESA CCI ice marginal lake inventory shows that the GrIML inventory has a more liberal classification of lakes (Table II). There are several reasons for this:

1. Thresholds for the SAR backscatter and VIS multi-spectral classification were modified slightly, relaxing the strict classification approach for the ESA CCI inventory
2. The GrIML inventory includes recently detached lakes, where lakes were manually checked for the ESA CCI inventory to remove these
3. On inspection of the GrIML inventory, there are many instances where a single lake in the ESA CCI inventory is represented as many polygons in the GrIML inventory. Post-processing is needed in the GrIML inventory to group common polygons together as single lakes

Table II. A comparison of lake classifications by drainage basin from the GrIML and ESA CCI ice marginal lake inventories

Drainage basin	**Number of unique GrIML inventory lakes**	**Number of unique ESA CCI inventory lakes**
Central west (CW)	238	144
Central east (CE)	313	-*
Periphery ice caps (IC)	975	948
Northeast (NE)	688	696
North (NO)	258	247
Northwest (NW)	313	246
Southeast (SE)	258	385
Southwest (SW)	1054	681
Total	**4097**	**3347**

*The ESA CCI ice marginal lake inventory dissolved the central east (CE) drainage basin into the northeast (NE) and southeast (SE) basins, therefore statistics from CE are not available (How et al., 2021)

An additional note of interest is that the GrIML inventory has minimal manual intervention compared to the ESA CCI inventory. The ESA CCI inventory had substantial manual intervention on lake polygons where classifications were limited by ice cover, snow and icebergs. The MEaSUREs Greenland Ice Mapping Project (GIMP) ice margin (Howat, 2017) was also modified for the ESA CCI inventory where the margin was clearly incorrect, such as in Nunatak areas. An example of this is presented in Fig. 4, where lakes were detected within inland Nunatak areas for the ESA CCI inventory but are not present in the GrIML inventory because the GIMP ice margin did not include these areas.

It is intended to perform manual interventions in the GrIML inventory to better match the ESA CCI inventory. However, these manual interventions will be documented in the dataset to ensure a level of reproducibility that was not present in the ESA CCI inventory.

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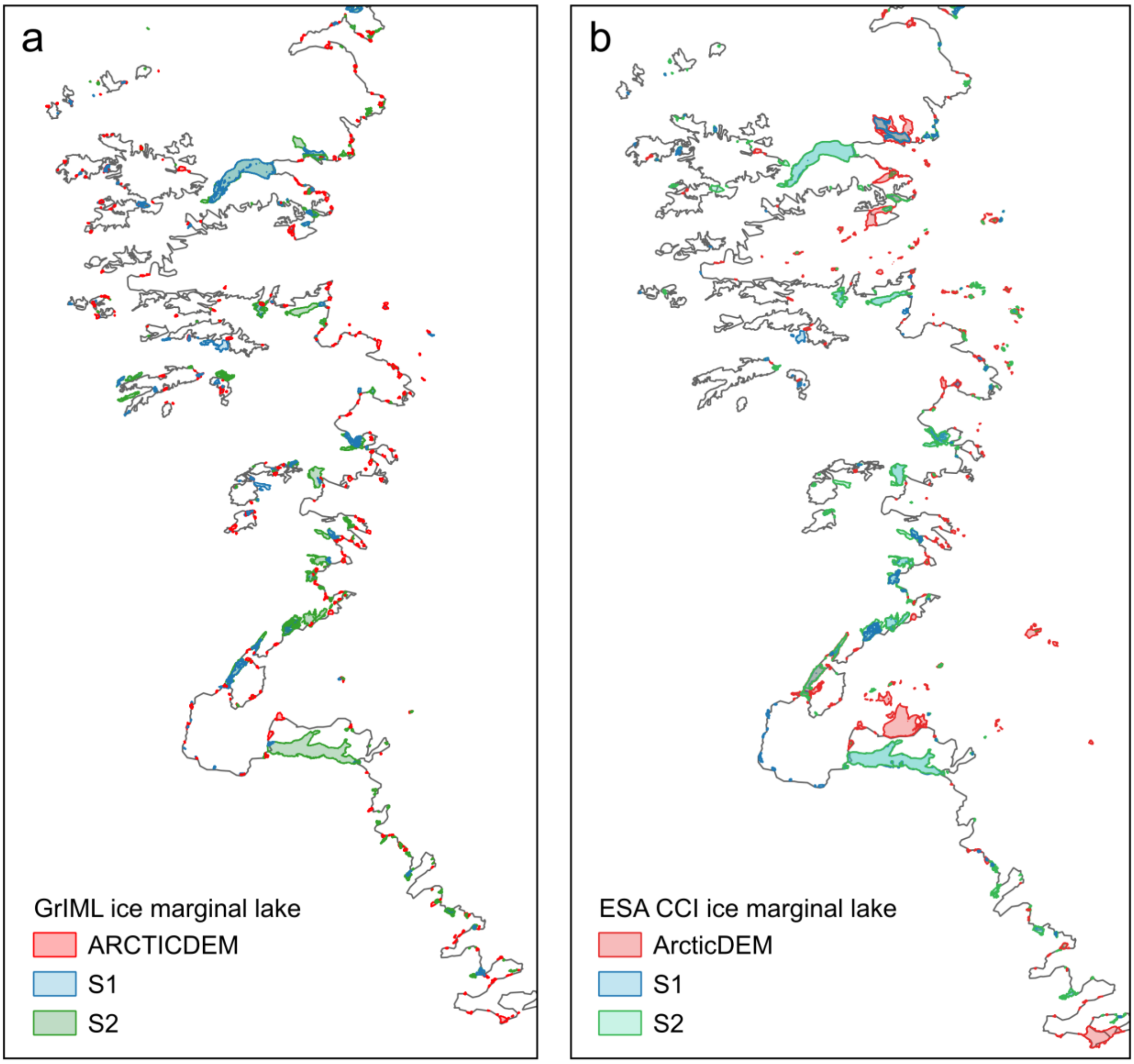

Figure 4: A comparison of the GrIML ice marginal lake inventory (a) with the ESA CCI ice marginal lake inventory (b) in the southwest (SW) drainage basin. The largest lake in this region is Kangaarsuup Tasersua at 71.3 km², detected in both inventories with the multi-spectral classification method. The ice sheet/ice cap drainage basin outlines are taken from Mouginot and Rignot (2019).

3.3 Time-series analysis

3.3.1 Nordbosø and lakes in the catchment of Eqalorutsit Kangilliit Sermiat, South Greenland

Several ice marginal lakes exist around the lateral margins of Eqalorutsit Kangilliit Sermiat, near Narsarsuaq in South Greenland. Fieldwork conducted in early 2023 (PI Nanna Karlsson, funded by Villum Fonden) focused on detecting submarine basal melt at the glacier terminus. Basal melt is suspected to have been detected, however, this may also be indicative of meltwater sourced from elsewhere. Given supraglacial lake formation does not occur until later in the melt season (i.e. May-September), the only other possible origin of meltwater in this glacier's catchment area is from the drainage of its ice marginal lakes. Therefore, this region is of interest to study to confirm whether melt discharge is related to basal melt and/or icemarginal lake drainages.

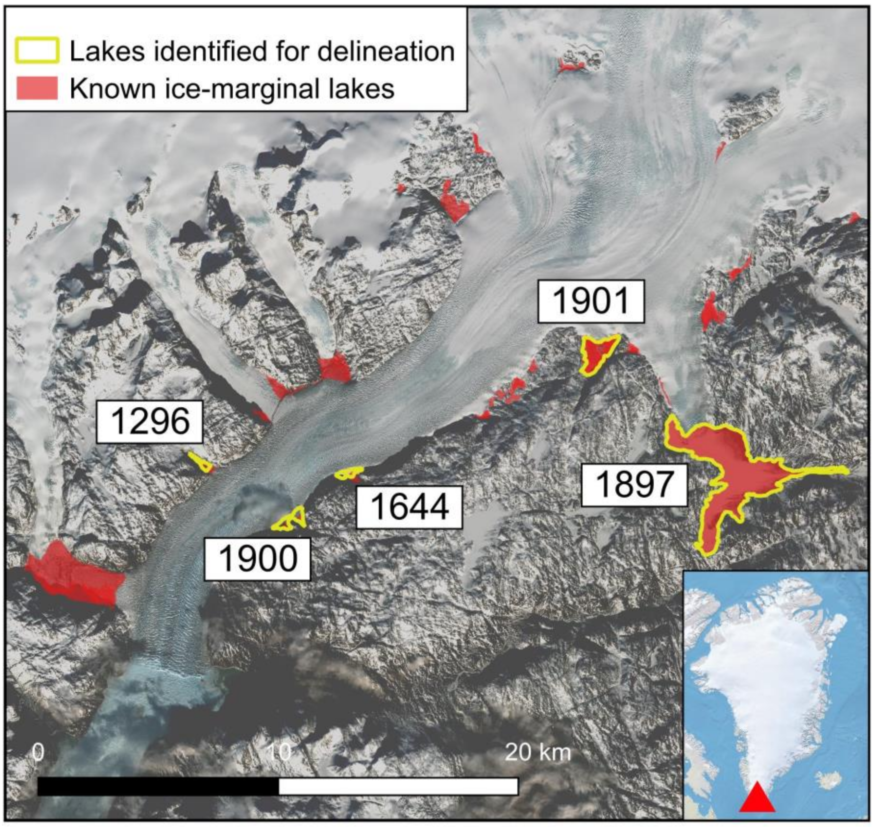

Figure 5: The five ice marginal lakes identified between January and April 2023 within the Eqalorutsit Kangilliit Sermiat catchment area. Known ice marginal lakes and lake identification numbers follow those defined by the 2017 inventory of Greenland ice marginal lakes (How et al., 2021). The background image is a visible composite from Sentinel-2 imagery captured on 06/03/2023. Taken from Karlsson et al. (In prep).

There are 21 lakes that share a margin with Eqalorutsit Kangilliit Sermiat, which were mapped in 2017 (How et al., 2021). Five of these lakes could be identified between January and April 2023, and were selected to construct time-series for, coinciding with the period when meltwater measurements were collected (Fig. 5). Four of the selected lakes are unnamed, whilst the largest lake is called Nordbosø. Little is known about the dynamics of these lakes, however, visual inspection through satellite image records suggest that none experience GLOF (glacial outburst flood) events or periods of substantial drainage.

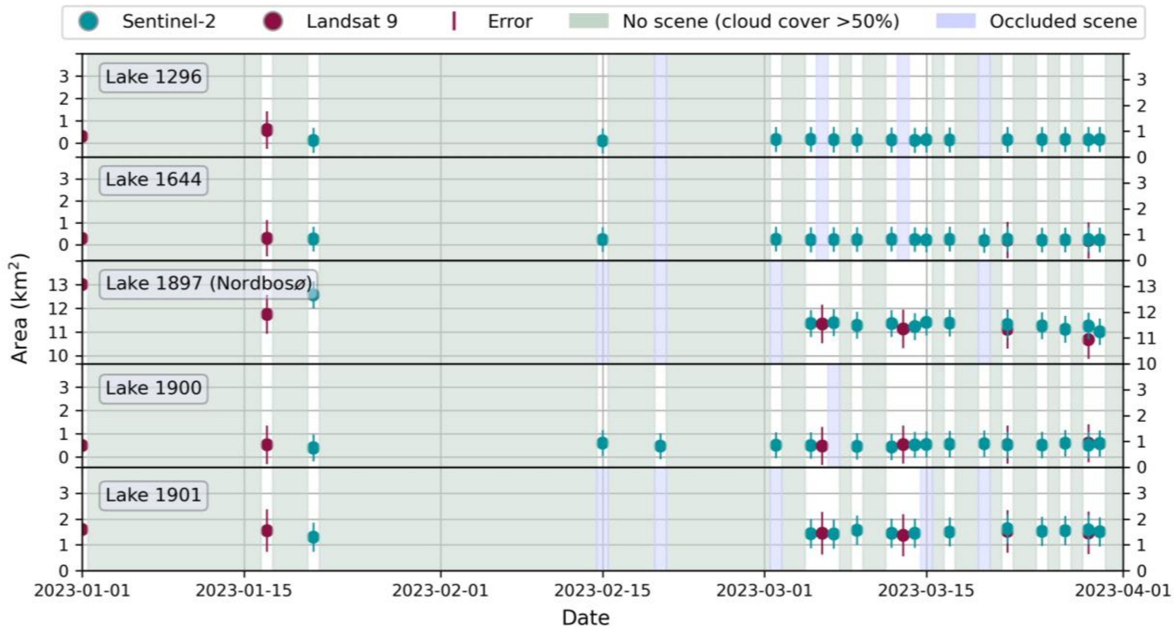

Figure 6: Time-series of lake area change around the Eqalorutsit Kangilliit Sermiat catchment area from Sentinel-2 and Landsat 9 imagery (corresponding lakes and identification numbers shown in Fig. 5). Taken from Karlsson et al. (In prep).

A time-series of surface areas was derived for the five ice marginal lakes identified between January and April 2023 (Fig. 6). The five lakes were delineated across 21 time steps, with 17 scenes from Sentinel-2 (10 m spatial resolution) and 6 scenes from Landsat 9 (30 m spatial resolution) where scenes had less than 50% cloud cover (Fig. 6). Occlusion of lake outlines occurred in some scenes due to localized cloud cover. The error estimate in lake surface area was quantified by repeated manual delineation of Nordbosø lake from the first Sentinel-2 and Landsat 9 image in the time-series; producing an error estimate of ±4.45% and ±6.31%, respectively.

The time-series presented in Fig. 6 suggests that the five ice marginal lakes in this region experienced limited variability in area between January and April 2023. There is also no evidence of any GLOF or full drainage events from the five lakes. The highest variability in surface lake area is evident at the beginning of the time-series record, which is likely to reflect the high snow cover at the beginning of the year. Variability in lake area is low in the latter half of the time-series, coinciding with higher data coverage from the Sentinel-2 record.

3.3.2 Hagen Bræ, North Greenland

An ice marginal lake located on Hagen Bræ (ESA CCI ice marginal lake inventory lake id 2531) has been observed with interesting GLOF drainage cycles, which may play a role in the glacier's surge-type behaviour (Fig. 7). The lake is an unnamed lake situated in a nunatak approximately 60 km upstream from the glacier terminus. The lake is approximately 25.81 sq km (about the area of JFK Airport), holding a substantial storage of glacial meltwater compared to nearby supraglacial lakes that form and drain seasonally. It is proposed to investigate the influence of GLOFs on ice dynamics at Hagen Bræ, using the constructed ice marginal lake time-series alongside other analysis, including surface and bed elevation estimations and ice velocities.

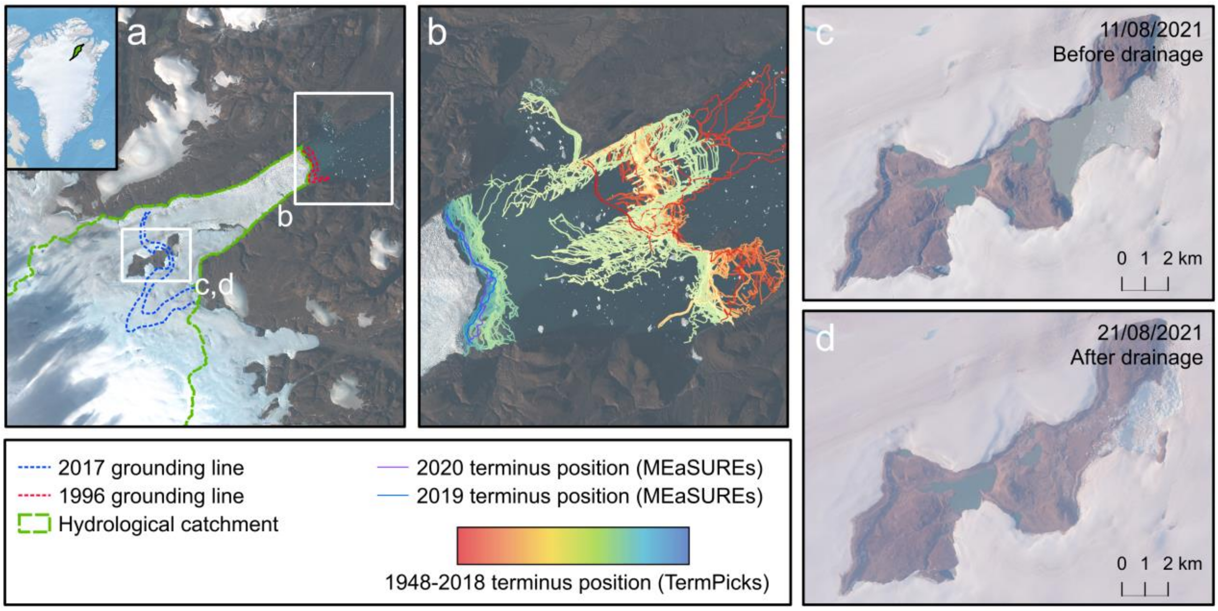

Figure 7: An overview of the Hagen Bræ glacier outlet from a Sentinel-2 visible composite image (captured 31/08/2023), with InSAR-derived grounding line positions from 1996 and 2017 (ESA CCI+ dataset) and hydrological catchment (modified to correspond with the terminus position at the time of Sentinel-2 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. Taken from How et al. (In prep).

Table III. 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*

Initial analysis of the lake conditions show that the lake drains roughly every 3 years (Table III), with the most recent drainage in 2021 coinciding with a dramatic slowdown in ice flow indicated by Sentinel-1 ice velocity records (Solgaard et al., 2021). A direct link between GLOF events and ice velocity slow-down could suggest an additional hydrological driver of Hagen Bræ's surging behaviour that has previously been alluded to in past remote sensing and modelling efforts (Solgaard et al., 2021; Winton et al., 2022).

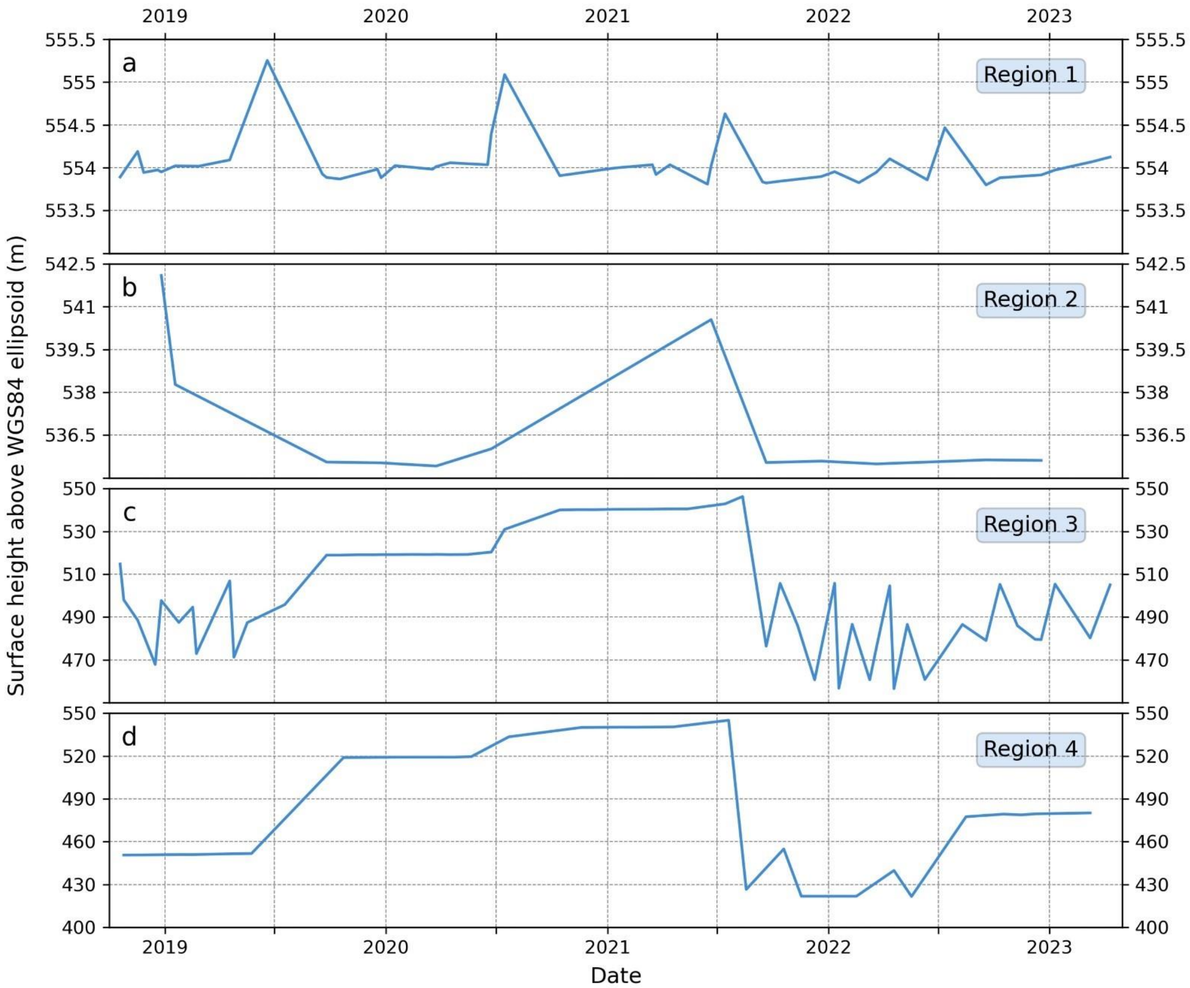

Figure 8: Time series depicting the evolving water surface height at Region 1 (a), Region 2 (b), Region 3 (c) and Region 4 (d). Regions 3 and 4 are within the larger lake, being the higher plateau and the lower plateau, respectively. Taken from How et al. (In prep).

Surface elevation estimations from ICESat-2 have been derived, extracting a series of measurements from tracks across the lake catchment split into four regions. Across the lake surface height time-series, values from all lake regions ranged between 400 and 550 m (above the WGS84 ellipsoid) (Fig. 8). The time-series shows a long period of filling occurred from July 2019 to August 2019 in regions 2, 3 and 4, after which a significant drainage event occurs with drop in the surface height of approximately 80-100 m. This large drainage event corresponds to the same event identified from Table II. With future efforts, it is hoped that a volume estimate for this drainage event can be calculated, which would be valuable for quantifying subglacial meltwater in the Hagen Bræ catchment.

4 CONCLUSIONS

To summarise, the first year of the GrIML project has yielded a workflow for automatically classifying ice marginal lakes from remotely sensed imagery and datasets. This workflow has been applied Greenland-wide to produce an inventory of ice marginal lakes for 2017. In addition, the workflow has been used to produce time-series of lake change which have provided insights into two glacier catchments in the north and south sectors of the Greenland Ice Sheet. The application of the workflow to these two sites has formed the basis of two academic publications that are in preparation.

The work plan for the second year of the GrIML project will see the continuation of the ice marginal lake inventory generation, with a series of inventories constructed for the Sentinel era (2016-2023). The ice marginal lake time-series analyses will continue at Eqalorutsit Kangilliit Sermiat and Hagen Bræ with the inclusion of other datasets, along with the selection and analysis of other lake sites that are of scientific and/or societal interest.

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Wiesmann, A. *et al.* (2021) ESA Glaciers Climate Change Initiative (Glaciers_cci): 2017 inventory of ice marginal lakes in Greenland (IIML), C*entre for Environmental Data Analysis* **V1**. http://doi.org/10.5285/7ea7540135f441369716ef867d217519

Winton, Ø. A. *et al.* (2022) Basal stress controls ice-flow variability during a surge cycle of Hagen Bræ, Greenland. *Journal of Glaciology* **68**(269), 503–517. https://doi.org/10.1017/jog.2021.111

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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 status and a possible future. *Geophys. Res. Lett.* 49 (12), 2022GL099276R. https://doi.org/10.1029/2022GL099276

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

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*

Karlsson, N. B., **How, P.**, *et al.* In-situ observations from the terminus of a marine-terminating glacier reveal freshwater fluxes during winter.

How, P. *et al.* 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 (pytrx1.2.4). *Zenodo*. https://doi.org/10.5281/zenodo.6624346

6.3 *Conference/invited talks and posters*

- "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).

6.4 Supervision

- Ph.D. supervision to Connie Harpur (University of Leeds) on "Controls on the dynamics of Greenlandic lake terminating glaciers", 2023-2026.
- M.Sc. thesis evaluator for Ethan Carr (University of Colorado Boulder) on "Ice Marginal Lakes in Greenland: Quantifying the Impact of Glacial Lake Outburst Flood Events", 2022-2024.