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5 Ice-marginal lakes associated with enhanced recession of the Greenland Ice 6 Sheet

7

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14 HIGHLIGHTS

- 15 • Prevalent and accelerating ice-margin recession in south-west Greenland from 1992
- 16 • Contrasting ice-marginal environments demonstrate a heterogeneous response to warming
- 17 • Lacustrine ice-margins recede faster than terrestrial, but slower than marine margins
- 18 • Lacustrine recession rates progressively outpaced terrestrial rates between 1987-2015
- 19 • Significant correlations between lake parameters and recession rates are identified

20

21 ABSTRACT

22 There has been a progressive increase in the number and area of ice-marginal lakes situated along the
23 south-western margin of the Greenland Ice Sheet (GrIS) since the 1980s. The increased prevalence of
24 ice-marginal lakes is notable because of their capacity to enhance mass loss and ice-margin recession
25 through a number of thermo-mechanical controls. Although such effects have been extensively
26 documented at alpine glaciers, an understanding of how ice-marginal lakes impact the dynamics of

27 the GrIS has been limited by a sparsity of observational records. This study employs the Landsat
28 archive to conduct a multi-decadal, regional-scale statistical analysis of ice-margin advance and
29 recession along a ~5000 km length of the south-western margin of the GrIS, incorporating its
30 terrestrial, lacustrine and marine ice-margins. We reveal an extended and accelerating phase of ice-
31 margin recession in south-west Greenland from 1992 onwards, irrespective of margin type, but also
32 observe considerable heterogeneity in the behaviour of the different ice-marginal environments.
33 Marine ice-margins exhibited the greatest magnitude and variability in ice-margin change, however
34 lacustrine termini were notable for a progressive increase in ice-margin recession rates from 1987 to
35 2015, which increasingly outpaced those measured at terrestrial ice-margins. Furthermore, significant
36 correlations were identified between lake parameters and rates of lacustrine ice-margin recession,
37 including lake area, latitude, altitude and the length of the lake – ice-margin interface. These results
38 suggest that ice-marginal lakes have become increasingly important drivers of ice-margin recession
39 and thus mass loss at the GrIS, however further research is needed to better parameterise the causal
40 connections between ice-marginal lake evolution and enhanced ice-margin recession. More widely, a
41 detailed understanding of the impacts of ice-marginal lakes on ice-margin dynamics across Greenland
42 is increasingly necessary to accurately forecast the response of the ice sheet to enhanced ice-marginal
43 lake prevalence and thus refine projections of recession, mass loss and sea level rise.

44

45 **KEYWORDS:** Greenland Ice Sheet; ice-marginal lake; proglacial lake; glacier dynamics; meltwater

46

47 **1. INTRODUCTION**

48 Since a period of near equilibrium mass balance in the 1980s, rates of mass loss at the Greenland Ice
49 Sheet (GrIS) have generally accelerated in response to increased atmospheric and oceanic warming
50 (Hanna et al., 2013; Shepherd et al., 2020). Over the same time period, enhanced rates of meltwater
51 runoff (Hanna et al., 2008; Trusel et al., 2018) have coincided with a progressive increase in the
52 number and area of ice-marginal lakes situated along the south-western margin of the GrIS (Carrivick

53 and Quincey, 2014; How et al. 2021). The presence of ice-marginal lakes is significant because of their
54 capacity to regulate ice-margin dynamics through a number of thermo-mechanical controls, including
55 the onset and promotion of calving (Carrivick and Tweed, 2013). In particular, ice-marginal lake
56 formation and expansion is typically associated with enhanced rates of mass loss and ice-margin
57 recession (e.g. Kirkbride, 1993; Boyce et al., 2007; Schomacker, 2010; Basnett et al., 2013; Brun et al.,
58 2019; King et al., 2019; Tsutaki et al., 2019; Liu et al., 2020; Sutherland et al., 2020). However, whilst
59 the effects of ice-marginal lakes on alpine glacier dynamics have been increasingly well-documented,
60 knowledge of their effects on the dynamics of ice sheets is presently limited by a sparsity of
61 observational records (Mallalieu et al., 2017, 2020). A detailed understanding of the impacts of ice-
62 marginal lakes on ice-margin dynamics across Greenland is therefore increasingly necessary to
63 accurately forecast the response of the ice sheet to enhanced ice-marginal lake prevalence and thus
64 further refine projections of mass loss and sea level rise.

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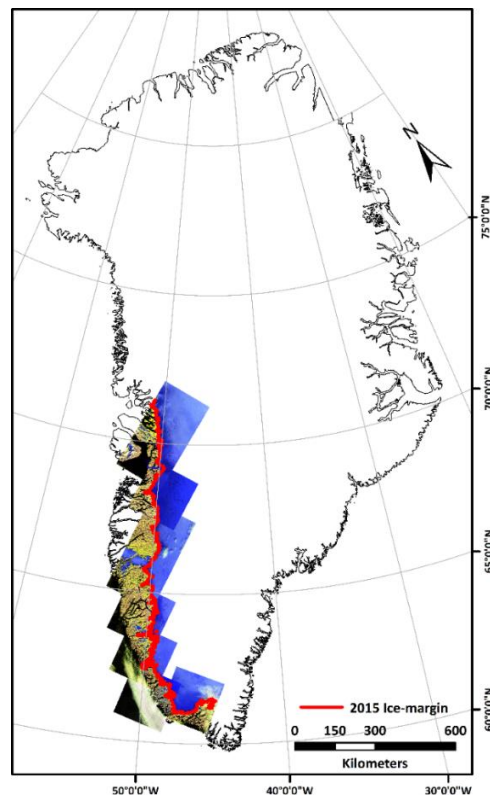
66 An analysis of outlet glacier extent by Warren (1991) revealed significant variability in the behaviour
67 of the terrestrial, lacustrine and marine outlets of the GrIS throughout the mid-20th century, despite
68 having undergone comparable climatic forcing. Both lacustrine and marine outlets were found to
69 exhibit much greater variability in frontal behaviour than their terrestrial counterparts due to their
70 partial decoupling from climatic forcing and the increased role of topographic and bathymetric
71 controls on terminus advance and recession. However, subsequent analyses of ice-margin behaviour
72 and extent in Greenland have omitted measurements from lacustrine ice-margins, instead focusing
73 on changes at the major marine-terminating outlets (e.g. Howat et al., 2008; Howat and Eddy, 2011;
74 Catania et al., 2018), and the terrestrial termini of peripheral glaciers and ice caps (PGICs) (e.g. Citterio
75 et al., 2009; Leclercq et al., 2012; Rastner et al., 2012; Bjørk et al., 2018). In addition, the few studies
76 that have incorporated measurements of ice-margin change from terrestrial outlets of the main ice
77 sheet typically include a sparse number of terrestrial data points (e.g. Moon and Joughin, 2008; Carr
78 et al., 2013; Mougnot et al., 2019), or concern a relatively limited footprint in south-east Greenland

79 (e.g. Kargel et al., 2012; Mernild et al., 2012). As a consequence, the relative magnitude of recent
80 changes at the terrestrial, lacustrine and marine margins of the GrIS remain unknown.

81

82 The long temporal record of the Landsat image archive, now extending into its fourth decade with the
83 launch of Landsat 8 (Roy et al., 2014), provides a unique opportunity to perform a multi-decadal,
84 regional-scale analysis of ice-margin extent for the disparate ice-marginal environments of the GrIS
85 between the 1980s and the present day. South-west Greenland is the optimal site for such an analysis
86 because: (i) it has the greatest regional concentration of land-terminating, and thus lacustrine,
87 margins of the GrIS (Figure 1); (ii) the region has experienced some of the highest increases in mean
88 annual air temperatures recorded in the Arctic since the 1990s (Carr et al., 2013; Ding et al., 2014);
89 and (iii) the region is forecast to undergo some of the greatest rates of ice-margin recession and
90 reductions in ice-cover over the next millennium (Aschwanden et al., 2019).

91



92

93 Figure 1. Study location in south-west Greenland. The spatial extent of the analysis is illustrated with
94 false-colour Landsat scenes from 2015 (see Table 1).

Table 1. Attributes of Landsat scenes used in this study.

Epoch	Sensor	Scene ID	Date of acquisition	Path	Row
2015	OLI	LC80010172015227LGN00	15/08/2015	1	17
	OLI	LC80020172015234LGN00	22/08/2015	2	17
	OLI	LC80040172015216LGN00	04/08/2015	4	17
	OLI	LC80050162015255LGN00	12/09/2015	5	16
	OLI	LC80060152015214LGN00	02/08/2015	6	15
	OLI	LC80060162015214LGN01	02/08/2015	6	16
	OLI	LC80070132015237LGN00	25/08/2015	7	13
	OLI	LC80070142015237LGN00	25/08/2015	7	14
	OLI	LC80080122015196LGN00	15/07/2015	8	12
	OLI	LC80100102015210LGN00	29/07/2015	10	10
	OLI	LC80100112015210LGN00	29/07/2015	10	11
2010	ETM+	LE70020172011231EDC00	19/08/2011	2	17
	ETM+	LE70040162009207EDC00	26/07/2009	4	16
	ETM+	LE70040172009207EDC00	26/07/2009	4	17
	ETM+	LE70060152011211ASN00	30/07/2011	6	15
	ETM+	LE70070132010231EDC00	19/08/2010	7	13
	ETM+	LE70070142011234EDC00	22/08/2011	7	14
	ETM+	LE70090112009210EDC00	29/07/2009	9	11
	ETM+	LE70090122010229EDC00	17/08/2010	9	12
	ETM+	LE70100102009217ASN00	05/08/2009	10	10
2005	ETM+	LE70020172004244ASN01	31/08/2004	2	17
	ETM+	LE70040162007202EDC00	21/07/2007	4	16
	ETM+	LE70040172007202EDC00	21/07/2007	4	17
	ETM+	LE70060142007216EDC00	04/08/2007	6	14
	ETM+	LE70060152006245EDC00	02/09/2006	6	15
	ETM+	LE70070132005217EDC00	05/08/2005	7	13
	ETM+	LE70090112007221EDC00	09/08/2007	9	11
	ETM+	LE70090122007221EDC00	09/08/2007	9	12
	ETM+	LE70110102005229EDC00	17/08/2005	11	10
2000	ETM+	LE70020172000217AGS00	04/08/2000	2	17
	ETM+	LE70040161999212EDC01	31/07/1999	4	16
	ETM+	LE70040171999212EDC01	31/07/1999	4	17
	ETM+	LE70060152001215AGS00	03/08/2001	6	15
	ETM+	LE70070132001190EDC00	09/07/2001	7	13
	ETM+	LE70070142001190EDC00	09/07/2001	7	14
	ETM+	LE70090112001188EDC00	07/07/2001	9	11
	ETM+	LE70090122001188EDC00	07/07/2001	9	12
	ETM+	LE70100102000257SGS00	13/09/2000	10	10
	ETM+	LE70110102000168EDC00	16/06/2000	11	10
1992	TM	LT50020171992219PAC00	06/08/1992	2	17
	TM	LT50040161992217PAC00	04/08/1992	4	16
	TM	LT50040171992217PAC00	04/08/1992	4	17
	TM	LT50050161993242PAC00	30/08/1993	5	16
	TM	LT50060141992263PAC00	19/09/1992	6	14
	TM	LT50060151992263PAC00	19/09/1992	6	15
	TM	LT50080121994170KIS00	19/06/1994	8	12
	TM	LT50080131994170PAC00	19/06/1994	8	13
	TM	LT40090111992212XXX02	30/07/1992	9	11
1987	TM	LT50050151987242XXX03	30/08/1987	5	15
	TM	LT50050161987258XXX01	15/09/1987	5	16
	TM	LT50060141987201XXX08	20/07/1987	6	14
	TM	LT50060151987201XXX08	20/07/1987	6	15
	TM	LT50070131987176XXX01	25/06/1987	7	13
	TM	LT40080121988146XXX01	25/05/1988	8	12
	TM	LT50090111985248KIS00	05/09/1985	9	11
	TM	LT40090121988169XXX01	17/06/1988	9	12
	TM	LT50110101987236KIS00	24/08/1987	11	10

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99 This study therefore aims to quantify changes in ice-margin extent at the terrestrial, lacustrine and
100 marine margins of the GrIS in south-west Greenland, and to investigate how the properties of ice-
101 marginal lakes relate to rates of lacustrine ice-margin change. The objectives comprise: (i) the
102 generation of an ice-marginal lake inventory and delineation of the ice sheet margin for 6 epochs at
103 approximately 5-year intervals between 1987 and 2015; (ii) the quantification of ice-margin advance
104 and recession at terrestrial, lacustrine and marine ice-margins between successive epochs; and (iii) a
105 statistical analysis of ice-marginal lake parameters and rates of change at lacustrine margins.

106

107 **2. DATA AND METHODS**

108 2.1 LANDSAT SCENE SELECTION

109 A total of 58 Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+) and Operational
110 Land Imager (OLI) scenes were downloaded from the USGS Global Visualisation Viewer to encompass
111 the predominantly terrestrial margins of the GrIS in south-west Greenland between the mid-1980s
112 and 2015 (Figure 1, Table 1). All scenes were Level 1TP (radiometrically calibrated and orthorectified)
113 products and possessed a horizontal ground resolution of 30 m. The scenes were selected to coincide
114 with the melt season (late May to early September) in order to minimise seasonal variability and to
115 also reduce the incidence of frozen lakes and snow cover along the ice-margin. Extensive cloud and/or
116 persistent snow cover in some years necessitated a flexible sampling interval for the acquisition of
117 scenes throughout the study period. Therefore, following the method of Carrivick and Quincey (2014),
118 scenes were assigned to one of 6 epochs (1987, 1992, 2000, 2005, 2010 and 2015), with 86 % of scenes
119 acquired within ± 1 year of their respective epoch, and the remaining scenes acquired within ± 2 years
120 (Table 1). Scenes in the 2005 and 2010 epochs were also selected to mitigate the effects of the failed
121 ETM+ Scan Line Corrector (SLC) by utilising the considerable scene overlap within the study area.
122 Where SLC failure induced stripes were unavoidable, gaps were filled via mosaicing with an unaffected

123 scene from the closest viable time period. Processing of the Landsat scenes was conducted in software
124 ENVI v.5.2 and Esri ArcMap v.10.3.1.

125

126 2.2 ICE-MARGINAL LAKE INVENTORY

127 The ice-marginal lake inventory used in this study was derived by refining the 1987-2010 lake dataset
128 mapped in Carrivick and Quincey (2014) and extending the duration of the survey to incorporate
129 Landsat scenes from 2015. Details of the scene processing are fully described and evaluated in
130 Carrivick and Quincey (2014), hence a synopsis is provided here. Scenes were classified by applying
131 the Normalised Difference Water Index (NDWI) (McFeeters, 1996) to the near infrared (NIR) and blue
132 bands of the respective TM, ETM+ and OLI spectral channels, where $NDWI = ((B_{NIR} - B_{Blue}) / (B_{NIR} + B_{Blue}))$
133 and B is the spectral channel. The blue, rather than the more established green, spectral channel was
134 employed because of its improved ability to discriminate water from snow and ice in cold
135 environments (Huggel et al., 2002). An upper NDWI threshold of -0.5 was used to automatically detect
136 lakes and a median filter (3×3 kernel) was used to reduce noise and remove isolated pixels. Classified
137 lakes were exported as polygons for quality assurance in ArcMap, with misclassified areas of cloud
138 and shadow manually corrected through comparison with scenes from adjacent epochs. Manual
139 digitisation was used to delineate several frozen lakes, accounting for ~0.5 % of the total lake dataset.
140 The analysis here was subsequently restricted to lakes that: (i) retained contact with the ice-margin;
141 (ii) were endorheic (with no visible outflow); and (iii) were greater than 25,000 m² in area. The ice-
142 contact and endorheic conditions were included to specifically consider the effect of meltwater
143 retention on ice-margin change.

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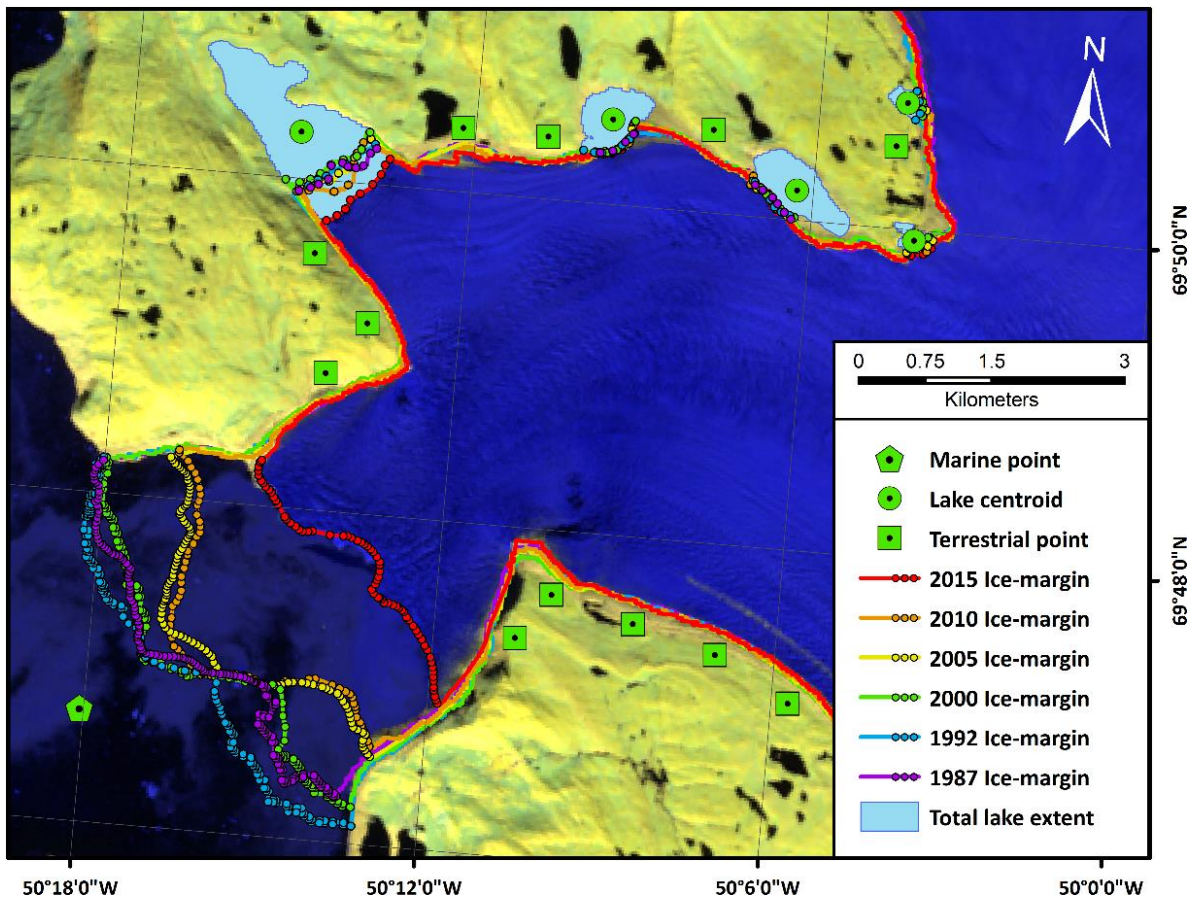
145 In order to establish a dataset of lake parameters, each lake was assigned a consistent identifier
146 throughout the study period by calculating the centroid of the total lake extent (the maximum outline
147 of a given lake across all epochs) (Figure 2). Lake areas were subsequently calculated within each
148 epoch, but lakes that lost ice-contact via drainage or ice-margin recession were discounted from the

149 dataset for the respective epoch(s). In the event of a partial lake drainage, only the lake basin that
150 maintained ice-contact was retained in the analysis (e.g. Figure 3). In addition, each lake was assigned
151 a persistence score (from 1-6) to indicate its permanence across the 6 epochs. The length of the
152 interface between individual lakes and the ice-margin was measured by calculating the geometric
153 intersection of lake polygons and the delineated ice-margin to within a tolerance of 30 m (Figure 3).
154 Finally, the latitude and altitude of each lake centroid was extracted from a Digital Elevation Model
155 (DEM) of the GrIS generated from 1985 aerial photography, with a ground resolution of 25 m and
156 horizontal and vertical accuracies of ± 10 m ± 6 m respectively (Korsgaard et al., 2016). The delineation
157 of lake extent was assumed to be accurate to within ± 1 pixel (30 m) of the true lake perimeter.
158 Consequently, the absolute error associated with each area measurement was dependent on lake size
159 and planform, and thus resulted in a declining power law relationship whereby the greatest errors
160 were associated with the smallest lakes. For example, lakes measuring 0.5 km^2 had an area uncertainty
161 of $\sim 9\%$, whilst lakes measuring $> 5 \text{ km}^2$ had an uncertainty of $< 3\%$.

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178 Figure 2. Example of dataset, comprising terrestrial, lacustrine and marine ice-margins, and the
179 respective fixed points/centroids used for measurements of ice-margin change. Small circles on
180 marine and lacustrine ice-margins represent the vertices over which distance measurements are
181 averaged. Total lake extent represents the maximum outline of each lake across all epochs. Basemap:
182 2015 false-colour Landsat OLI scene.

183 [DOUBLE COLUMN WIDTH]

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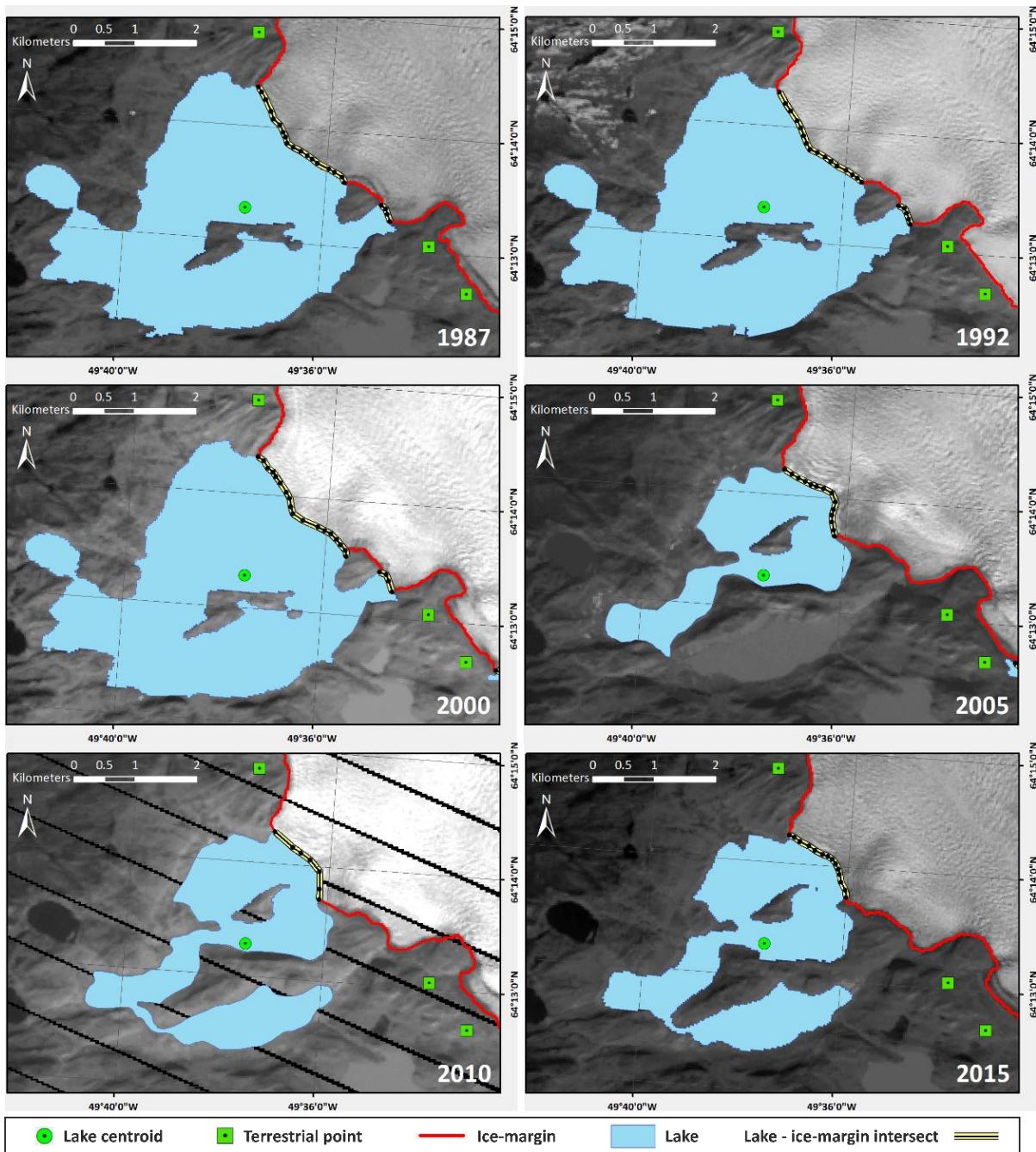
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Figure 3. Example of temporal variation in lake area and lake – ice-margin intersect over the survey period. In particular note the partial lake drainage between 2000 and 2005, and subsequent refilling.

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2.3 ICE-MARGIN DELINEATION

197 The ice sheet margin in south-west Greenland was delineated by using the green and shortwave
198 infrared (SWIR) bands of the respective TM, ETM+ and OLI spectral channels to classify scenes with
199 the Normalised Difference Snow Index (NDSI) (Hall et al., 1995), where $NDSI =$
200 $((B_{Green} - B_{SWIR}) / (B_{Green} + B_{SWIR}))$. An NDSI threshold of 0.45 ± 0.1 was used to classify areas of snow and
201 ice on a scene by scene basis with the aim of minimising subsequent manual post-processing. Due to
202 the similar spectral properties of snow, ice and water in the green and SWIR spectral bands, an
203 additional threshold of 0.45 was applied in the respective NIR band to mask out water bodies in the
204 ice-marginal environment and thus improve the accuracy of ice-margin delineation. A median filter
205 (3x3 kernel) was also applied to reduce noise and remove small snow patches. Manual editing was
206 subsequently employed to refine the delineated ice-margins in isolated areas affected by shadow,
207 debris cover and late-lying snow. Consistent mapping of the ice-margin was achieved in these regions
208 through consultation with scenes from neighbouring epochs and high resolution DigitalGlobe imagery
209 in Google Earth. Finally, delineated ice-margins in adjacent scenes were merged to generate a single
210 ice-margin for south-west Greenland within each epoch (Figures 1, 3), which were subsequently used
211 to derive the measurements of ice-margin advance and recession detailed in Section 2.4.
212 Measurements of total ice-margin length, comparable to the length of the lake – ice-margin intersects
213 detailed in Section 2.2, were generated by smoothing the delineated ice-margins to a tolerance of
214 30 m. Given that all results presented here are regionally aggregated, it is assumed that any over-
215 estimation of the ice-margin position is cancelled out by an equal and opposite under-estimation, and
216 uncertainty in the ice-margin positions is therefore not specifically assessed for these bulk figures.

217

218 2.4 MEASUREMENTS OF ICE-MARGIN CHANGE

219 Rates of ice-margin advance and recession between successive epochs were calculated by measuring
220 changes in ice-margin position relative to a series of fixed reference points across the study period.
221 Existing techniques for measuring changes in glacier extent have been primarily developed to quantify
222 changes in the position of glacier termini occupying troughs (e.g. Lea et al., 2014), and are thus

223 unsuited to analysing changes at lacustrine margins which typically occupy a greater diversity of ice-
224 marginal environments, particularly the lateral margins of outlet glaciers (cf. Figure 2). For example,
225 techniques that measure change along the centre-line of the glacier (e.g. Bevan et al., 2012; Mernild
226 et al., 2012) are not applicable at the majority of lacustrine margins. In addition, the highly dynamic
227 nature of many lake – ice-margin interfaces (cf. Figure 3) prevents the use of fixed boxes to calculate
228 area averaged advance or recession between successive epochs (e.g. Howat and Eddy, 2011; Hill et
229 al., 2018). Therefore, changes in the extent of lacustrine and marine ice-margins here were measured
230 using the bow method outlined in Bjørk et al. (2012). The centroids of the total lake extents were used
231 as fixed reference points from which to measure distances to the respective lake – ice-margin intersect
232 within each epoch, with a series of points established on the vertices of each intersect to permit the
233 calculation of a mean lake centroid – intersect distance (Figure 2). Rates of ice-margin advance or
234 recession were then calculated by differencing the mean distance values in successive epochs and
235 dividing by the interval duration. Consequently, rates of change at lacustrine margins were only
236 generated when a lake was present in two or more successive epochs. In the rare instances in which
237 a lake – ice-margin intersect was manifest in multiple sections (e.g. Figure 3) the loss/addition of
238 intersect sections between successive epochs resulted in small under- and over-estimates of ice-
239 margin recession respectively, which collectively had a negligible effect on the aggregated measures
240 of lacustrine margin change. Changes in the extent of marine margins were measured in the same
241 manner as lacustrine margins by establishing fixed marine points in front of each terminus and
242 calculating changes in mean distance between the marine points and respective marine margin
243 vertices in successive epochs (Figure 2). Changes at terrestrial margins were calculated by creating a
244 series of fixed points at 1 km intervals along a 250 m buffer of the delineated 1992 ice-margin.
245 Distances between the fixed terrestrial points and the proximal point on the terrestrial margin were
246 measured using proximity analysis and subsequently differenced to calculate rates of advance and
247 recession between successive epochs.

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249 2.5 STATISTICAL ANALYSES

250 Data were analysed using multivariate regression methods in R v.3.6.0 (R Core Team, 2019) to: (i)
251 investigate differences in rates of change at terrestrial, lacustrine and marine ice-margins; and (ii)
252 assess the influence of lake parameters on rates of change at lacustrine margins. Two linear mixed-
253 effects models (LMMs) were fitted (Bates et al., 2015) using the rate of ice-margin change as the
254 dependent variable in both models. One data point from Jakobshavn Isbrae was omitted due to its
255 extreme outlying status (> 2 km recession between the 2000 and 2005 epochs). The repeated
256 sampling of the same sites across epochs was accounted for by including location as a random effect.
257 LMM 1 compared rates of change at the disparate margin types, and included: ice-margin type
258 (lacustrine, marine, terrestrial); epoch; and latitude as independent variables (with latitudinal data
259 included to control for the spatial clustering of particular margin types along the ice-margin). LMM 2
260 assessed rates of change at lacustrine margins, and included the independent variables: latitude;
261 altitude; lake area; intersect length; persistence; and epoch. All independent variables were tested for
262 multicollinearity prior to model fitting; however, lake area and intersect length failed to meet this
263 assumption ($|r| > 0.7$; Dormann et al., 2013). Consequently, two alternate versions of LMM 2 were
264 fitted to accommodate lake area and intersect length respectively.

265

266 **3. RESULTS**

267 3.1 MODEL FIT

268 Testing of the fitted LMMs for normality and heteroscedasticity revealed that the distribution of the
269 residuals was heavy-tailed. Consequently, additional Robust LMMs were constructed to assess the
270 impact of outliers on model fit (Koller, 2006). The resultant similarity of the respective LMM and
271 Robust LMM coefficients (Table 2) indicated that the outliers had a limited effect on the fit of the
272 models, therefore the outputs of the initial LMMs are presented henceforth.

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276 Table 2. LMM and Robust LMM model variables and coefficients.

LMM 1*			LMM 2(a)			LMM 2(b)		
Ind. variables	LMM	Robust LMM	Ind. variables	LMM	Robust LMM	Ind. variables	LMM	Robust LMM
Epoch	-0.120	-0.081	Latitude	0.065	0.051	Latitude	0.068	0.049
Type:Marine	-2.637	-0.612	Altitude	0.132	0.074	Altitude	0.132	0.073
Type:Terrestrial	0.215	0.100	Lake area	-0.191	-0.074	Intersect length	-0.223	-0.095
Latitude	0.020	0.012	Epoch	-0.157	-0.142	Epoch	-0.153	-0.142
			Persistence	0.030	0.021	Persistence	0.094	0.049

277 * Note reference values for categorical variables 'Type' in LMM 1 are Lacustrine.

278 [DOUBLE COLUMN WIDTH]

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280 3.2 ICE-MARGIN CHANGE AT TERRESTRIAL, LACUSTRINE AND MARINE MARGINS

281 The ice-margins mapped in this study delineate a ~5000 km length of the south-western margin of the
282 GrIS. Cumulative totals of ice-margin type remained broadly consistent between 1987 and 2015, with
283 ~89 % of the ice-margin in the study area terminating in a terrestrial setting, ~8 % in a lacustrine setting
284 and ~3 % in a marine setting (Table 3). The number of measurements of ice-margin change between
285 successive epochs was substantial throughout the study period, with each period incorporating
286 measurements from between 22 to 35 marine margins, 353 to 439 lacustrine margins and 2469 to
287 3325 terrestrial margins (Table 4). From 1992 onwards, mean change at all margin types was negative,
288 signifying an extended duration of ice-margin recession in south-west Greenland. However, positive
289 values of mean change between 1987 and 1992 reveal an earlier period of ice-margin advance at both
290 terrestrial and marine margins, although mean change at lacustrine margins remained negative
291 (Table 4).

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297 Table 3. Summary statistics of ice-margin composition in south-west Greenland throughout the study
 298 period.

Epoch	Total ice-margin length		Terrestrial ice-margin length		Lacustrine ice-margin length		Marine ice-margin length	
	km	% of total	km	% of total	km	% of total	km	% of total
1987	3722*	100.00	3306	88.82	319	8.56	98	2.63
1992	5029	100.00	4500	89.47	398	7.91	132	2.62
2000	5019	100.00	4466	88.98	421	8.38	132	2.64
2005	4916	100.00	4377	89.04	405	8.24	133	2.71
2010	4966	100.00	4429	89.19	402	8.10	135	2.71
2015	4932	100.00	4345	88.10	434	8.80	153	3.10

299 * The reduced length of the 1987 ice-margin is due to the unavailability of Landsat TM scenes from the southern end of the study
 300 area in the years 1985-1988.

301 [DOUBLE COLUMN WIDTH]

302

303 Table 4. Summary statistics of ice-margin change in south-west Greenland throughout the study
 304 period. Note positive and negative values represent ice-margin advance and recession respectively.

Period	Terrestrial ice-margins			Lacustrine ice-margins			Marine ice-margins		
	n	Mean change (m)	Mean annual change (m)	n	Mean change (m)	Mean annual change (m)	n	Mean change (m)	Mean annual change (m)
1987-1992	2469	5.8	1.2	353	-5.3	-1.1	22	96.3	19.3
1992-2000	3325	-1.4	-0.2	439	-13.0	-1.6	35	-250.6	-31.3
2000-2005	3325	-24.0	-4.8	414	-28.3	-5.7	35	-640.3	-69.7
2005-2010	3325	-15.3	-3.1	401	-32.2	-6.4	35	-197.6	-39.5
2010-2015	3325	-13.8	-2.8	374	-57.3	-11.5	35	-417.8	-83.6

305 [DOUBLE COLUMN WIDTH]

306

307 LMM 1 identified a significant negative correlation between rate of ice-margin change and epoch
 308 ($p < 0.001$), signifying increasing rates of ice-margin recession in south-west Greenland between 1987
 309 and 2015, irrespective of margin type (Table 5). The model also identified significant differences
 310 between rates of change at lacustrine and marine margins ($p < 0.001$), and lacustrine and terrestrial
 311 margins ($p < 0.001$) (Table 5). Marine margins exhibited both the greatest mean rates of ice-margin
 312 recession and the greatest variability in frontal behaviour throughout the study period, with rates of
 313 advance and recession at several termini exceeding 100 m per year (Table 4, Figure 4a). The magnitude

314 and variability of changes at terrestrial and lacustrine margins were more comparable, although
 315 changes at lacustrine margins were less clustered around the median and typically more negative than
 316 their terrestrial counterparts (Table 4, Figure 4b). Notably, although rates of recession increased at
 317 both terrestrial and lacustrine ice-margins between 1987 and 2015, recession at lacustrine margins
 318 increasingly outpaced that of terrestrial margins throughout the survey period (Figure 5).

319

320 Table 5. LMM results. Significant relationships are highlighted in bold.

LMM No.	Ind. Variables	Estimate	Std. Error	t value	95 % Confidence intervals		p value
					lower	upper	
1	(Intercept)	-0.167	0.024	-6.975	-0.214	-0.120	< 0.001
	Epoch	-0.120	0.007	-17.360	-0.134	-0.107	< 0.001
	Type:Marine*	-2.637	0.088	-29.907	-2.809	-2.464	< 0.001
	Type:Terrestrial*	0.215	0.025	8.466	0.165	0.265	< 0.001
	Latitude	0.020	0.008	2.453	0.004	0.036	0.014
2(a)	(Intercept)	-0.039	0.040	-0.986	-0.117	0.039	0.324
	Latitude	0.065	0.026	2.438	0.013	0.116	0.015
	Altitude	0.132	0.025	5.241	0.083	0.181	< 0.001
	Area	-0.191	0.022	-8.687	-0.234	-0.148	< 0.001
	Epoch	-0.157	0.022	-7.215	-0.200	-0.114	< 0.001
	Persistence	0.030	0.103	0.293	-0.171	0.231	0.770
2(b)	(Intercept)	-0.072	0.040	-1.796	-0.150	0.006	0.073
	Latitude	0.068	0.026	2.576	0.016	0.119	0.010
	Altitude	0.132	0.025	5.299	0.084	0.181	< 0.001
	Intersect length	-0.223	0.022	-10.026	-0.267	-0.180	< 0.001
	Epoch	-0.153	0.022	-7.085	-0.196	-0.111	< 0.001
	Persistence	0.094	0.103	0.917	-0.107	0.295	0.359

321 * Note reference values for categorical variables 'Type' are lacustrine.

322 [DOUBLE COLUMN WIDTH]

323

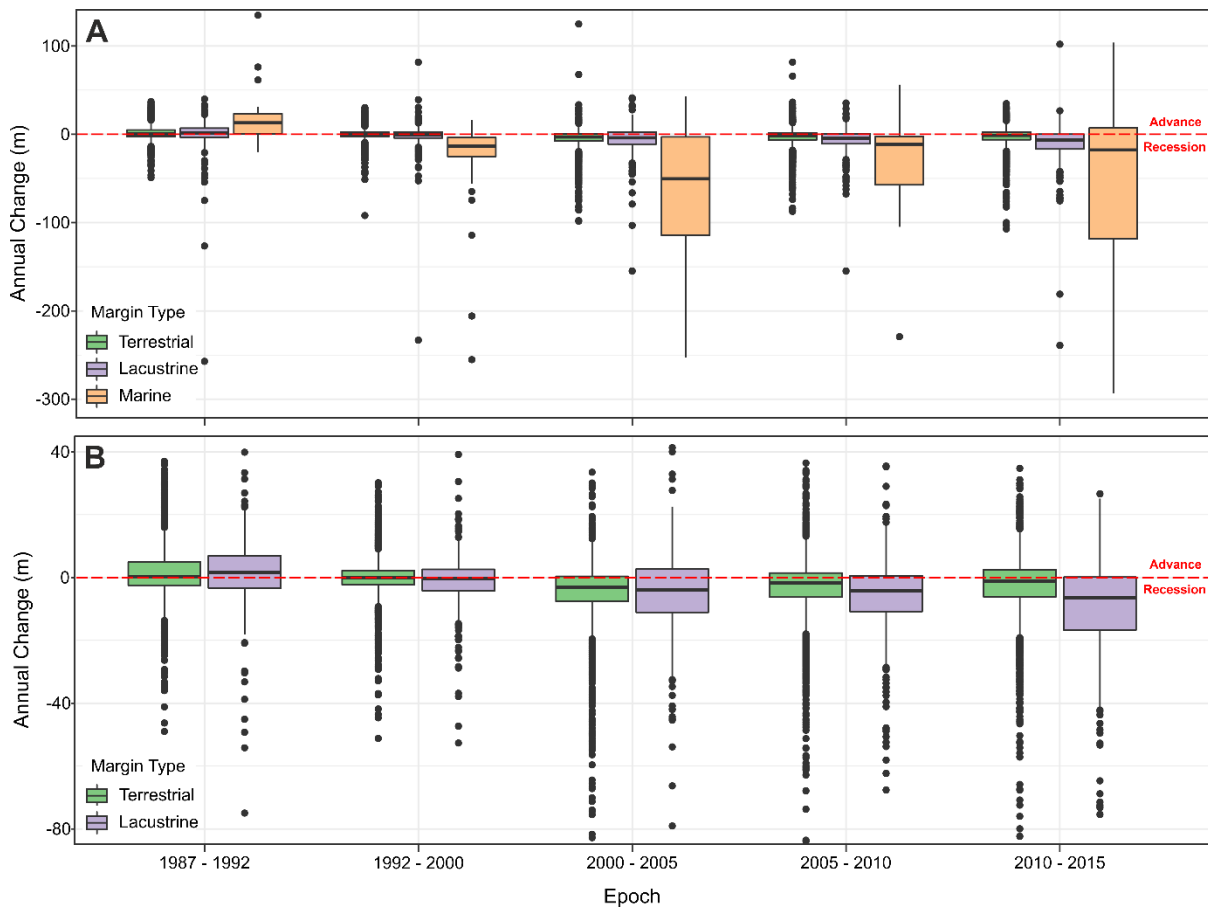
324

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328



329

330 Figure 4. Box plots of ice-margin change throughout the study period at: (a) terrestrial, lacustrine and
 331 marine margins; and (b) terrestrial and lacustrine margins only. Note positive and negative values of
 332 annual change represent ice-margin advance and recession respectively. To improve clarity, 7 and 21
 333 outlying data points have been cropped from panels (a) and (b) respectively.

334 [DOUBLE COLUMN WIDTH]

335

336

337

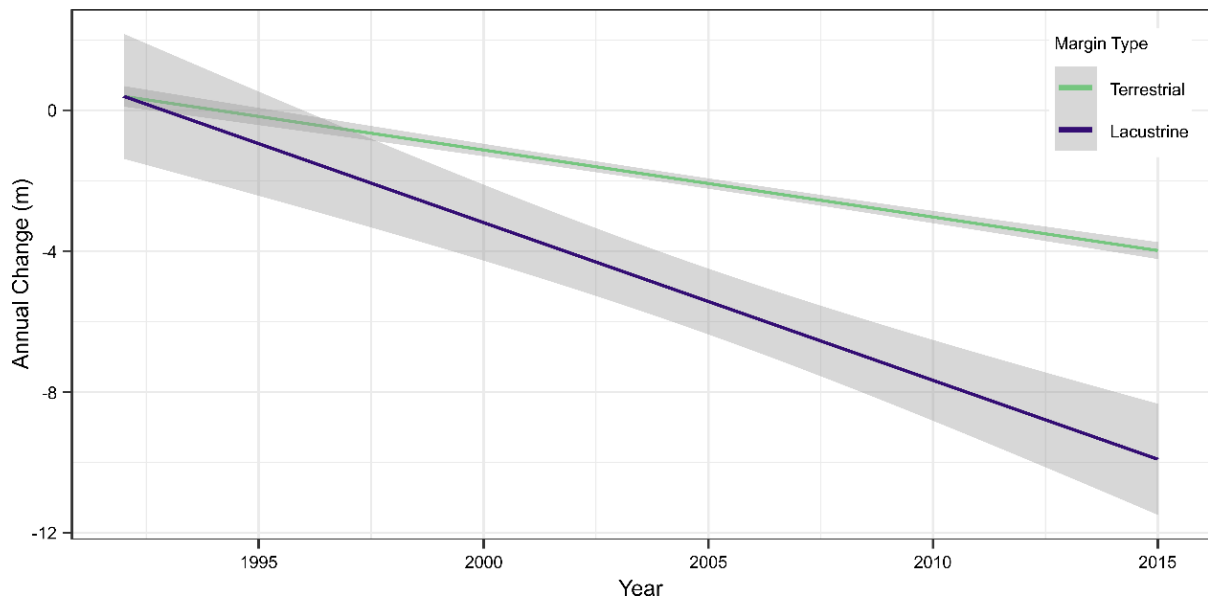
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343

344 Figure 5. Linear regression of annual change and year, showing trends in ice-margin recession at
 345 terrestrial and lacustrine margins. The final year of each epoch has been used to plot the linear
 346 relationship. Grey shading represents the 95 % confidence interval. Individual data points have been
 347 removed to improve clarity (terrestrial n = 15769; lacustrine n = 1981).

348 [DOUBLE COLUMN WIDTH]

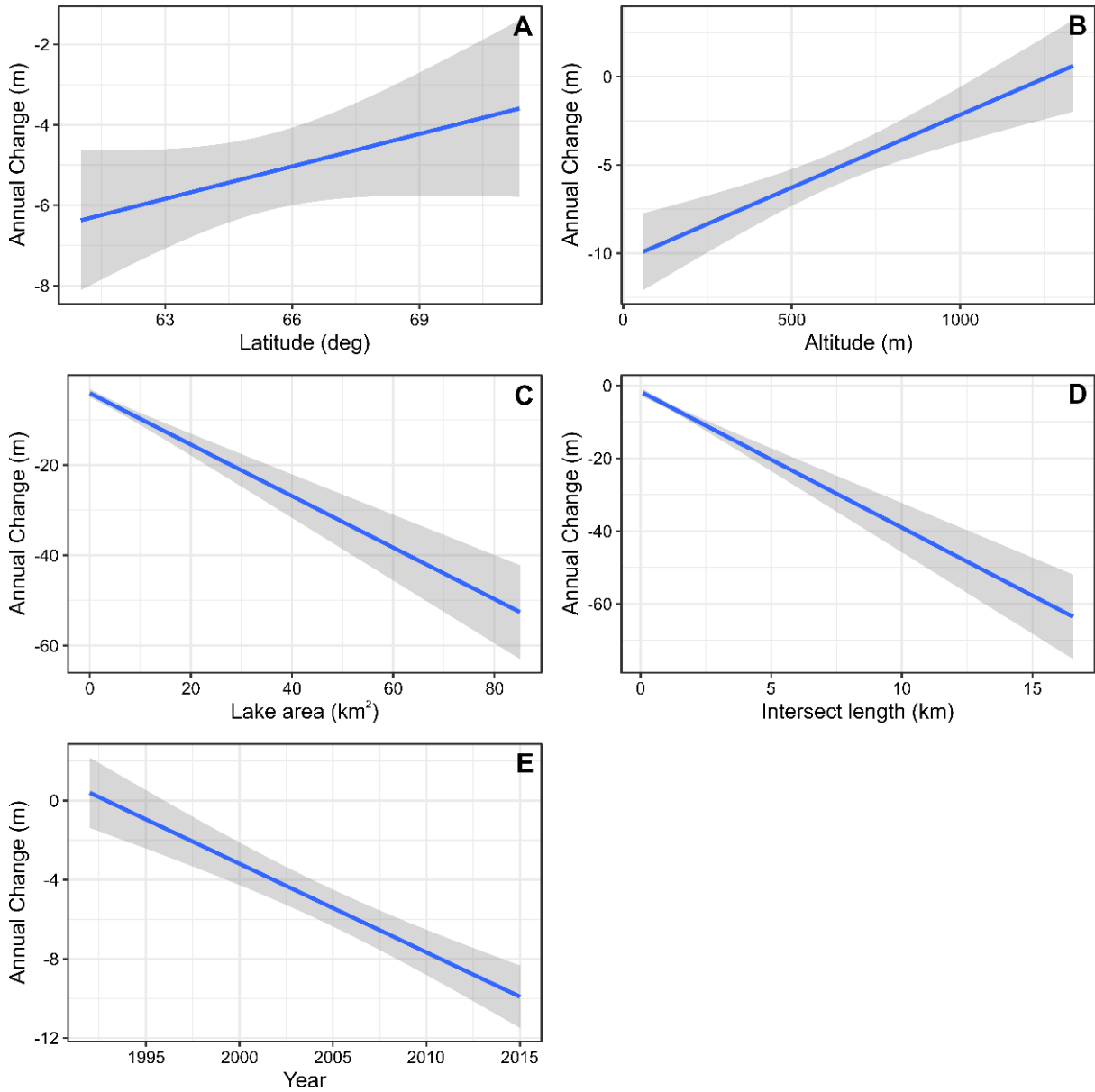
349

350 3.3 CONTROLS ON LACUSTRINE ICE-MARGIN CHANGE

351 Both variants of LMM 2 identified a number of significant relationships between lake parameters and
 352 rates of change at lacustrine margins (Table 5). The significant positive correlation between latitude
 353 and rate of change ($p < 0.05$) indicates that ice-margin recession was accentuated at lower latitudes
 354 (Figure 6a). Altitude was also found to act as a control on ice-margin change ($p < 0.001$), with increased
 355 rates of recession at lower altitudes (Figure 6b). Both lake area ($p < 0.001$) and intersect length
 356 ($p < 0.001$) possessed a similar significant negative correlation with rate of change, demonstrating that
 357 increased rates of ice-margin recession are associated with larger lakes and longer lake – ice-margin
 358 interfaces (Figures 6c, 6d). Finally, there was a significant negative correlation between epoch and
 359 rate of change ($p < 0.001$), signifying that rates of recession at lacustrine margins increased

360 throughout the duration of the study (Figure 6e). No significant correlation was found between
361 persistence and rate of ice-margin change.

362



363

364 Figure 6. Linear regressions of annual change at lacustrine margins and lake parameters, comprising:
365 (a) latitude; (b) altitude; (c) lake area; (d) intersect length; and (e) year. Note the final year of each
366 epoch has been used to plot the linear relationship in (e). Grey shading represents the 95 % confidence
367 interval. Individual data points have been removed to improve clarity (n = 1981).

368 [DOUBLE COLUMN WIDTH]

369

370 **4. DISCUSSION**

371 **4.1 ICE-MARGIN CHANGE IN SOUTH-WEST GREENLAND**

372 The temporal patterns of ice-margin advance and recession that we record in south-west Greenland
373 broadly reflect previously-documented changes in ice sheet mass balance. Notably, in contrast to the
374 mean ice-margin recession observed at all margin types post-1992, a mean advance at terrestrial and
375 marine margins, and concurrent minima of lacustrine margin recession, is evident between 1987 and
376 1992 (Table 4). Although this distinction could be accentuated by the unavailability of satellite imagery
377 from the southern reaches of the survey area in 1987 (Table 3), this pattern coincides with existing
378 records of outlet glacier advance and general ice sheet expansion in the southern and western GrIS
379 during the 1980s (e.g. Weidick, 1991; Zwally, 1989; Van Tatenhove et al., 1995; Knight et al., 2000)
380 following a period of net mass gain in the preceding decade (Mouginot et al., 2019). Similarly, the
381 period of ice-margin recession recorded post-1992 occurs following a transition to net mass loss at
382 the GrIS in the 1980s (Mouginot et al., 2019), and is sustained through a further fivefold increase in
383 the rate of mass loss between the 1990s and 2010 (Shepherd et al., 2020). However, the statistically
384 significant differences between rates of change at the disparate margin types (Table 5) and
385 considerable differences in variability of frontal behaviour (Figure 4) are indicative of heterogeneous
386 responses at the respective terrestrial, lacustrine and marine margins of the GrIS, despite undergoing
387 comparable climatic forcing over the survey duration.

388

389 The relative magnitude and variability of the changes recorded at the disparate ice-marginal
390 environments in this study are similar to those observed at the western margins of the GrIS in the mid-
391 20th century by Warren (1991), in which marine margins were found to exhibit the greatest magnitude
392 and variability in frontal behaviour, and terrestrial margins the least. Because terrestrial termini lack
393 oceanic or lacustrine forcing, changes in ice-margin extent are typically a delayed response to regional
394 climatic forcing, with inter-glacier variability arising from glacier-specific factors, including: glacier
395 geometry; hypsometry; debris-cover; and local climatic conditions (e.g. Pelto and Hedlund, 2001;

396 Scherler et al., 2011; Davies et al., 2012; Sakai and Fujita, 2017; Lovell et al., 2019). Consequently, the
397 relatively limited variability in frontal behaviour at the terrestrial margins of the GrIS, in comparison
398 to its marine margins, was expected (Figure 4a), and has been similarly observed in analyses of outlet
399 glacier and PGIC extent in south-eastern Greenland over the same period (e.g. Mernild et al., 2012).
400 Furthermore, the low magnitude of the changes observed at terrestrial margins compares favourably
401 with existing records of terrestrial frontal behaviour in western Greenland in the 1990s and 2000s (e.g.
402 Moon and Joughin, 2008; Carr et al., 2013).

403

404 In comparison to terrestrial margins, marine termini demonstrated considerably greater magnitude
405 and variability in frontal behaviour over the duration of the study, with a mean annual advance of
406 19 ma^{-1} between 1987 and 1992, succeeded by mean annual recessions exceeding 31 ma^{-1} in all
407 remaining periods (Table 4). In addition, the mean changes masked considerable complexity in the
408 behaviour of individual marine terminating glaciers, with advances and recessions in the order of 10s
409 and 100s of ma^{-1} respectively becoming increasingly prevalent from 2000-2005 onwards (Figure 4a).
410 Isolating the exact drivers of change at marine ice-margins is challenging due to the complexities and
411 interactions of both atmospheric and oceanic forcings, as well as glacier-specific controls including
412 terminus geometry and bathymetry (McFadden et al., 2011; Porter et al., 2018). However, oceanic
413 forcing is increasingly recognised as a key control on the dynamics of the marine outlets of the GrIS
414 (Seale et al., 2011; Straneo and Heimbach, 2013). Accordingly, the observed transition from mean
415 terminus advance to mean terminus recession at marine margins in 1992-2000 coincides with
416 recorded increases in subsurface ocean temperatures along the west coast of Greenland in the mid-
417 1990s (Myers et al., 2007; Holland et al., 2008), which are hypothesised to have triggered the collapse
418 of several floating termini and a subsequent phase of regional marine ice-margin recession in response
419 to debuttressing (e.g. Joughin et al., 2012). A further increase in marine ice-margin recession observed
420 in this study in the early 2000s also concurs with similar observations from the same time period at

421 marine terminating outlets in south-eastern Greenland (Mernild et al., 2012) and across the wider ice
422 sheet (Moon and Joughin, 2008; Howat and Eddy, 2011).

423

424 Despite mean changes in marine ice-margin extent being approximately an order of magnitude
425 greater than those recorded at terrestrial and lacustrine ice-margins between 1987 and 2015, caution
426 is necessary when interpreting and comparing the frontal behaviour of the disparate ice-marginal
427 environments of the GrIS. In particular, marine ice-margins constitute by far the smallest component
428 of the overall dataset ($n = 22-35$), and typically exhibit seasonal variations in terminus advance and
429 recession that can be challenging to control for using multi-annual snapshots of terminus position
430 (Schild and Hamilton, 2013). Furthermore, the relatively similar magnitudes of change observed at
431 terrestrial and lacustrine termini conceal a notable divergence in the behaviour of the respective
432 margin types over the duration of the study. In particular, the persistently negative values of mean
433 changes at lacustrine margins, coupled with a progressive increase in their magnitude and their
434 increased outpacing of change at terrestrial margins (Table 4, Figure 5), could be indicative of
435 amplified lacustrine forcing and mass loss at the lake terminating margins of the GrIS between 1987
436 and 2015.

437

438 4.2 LACUSTRINE ICE-MARGIN RECESSION

439 The observed dissimilarities in the frontal behaviour of the terrestrial and lake terminating margins of
440 the GrIS over the course of the study can be explained by the impact of lacustrine forcing on ice-margin
441 dynamics. In particular, lake formation has significant implications for processes and rates of mass loss
442 at ice-margins through the onset of both calving (Kirkbride, 1993; Motyka et al., 2003) and subaqueous
443 melt (Eijpen et al., 2003; Haresign and Warren, 2005; Truffer and Motyka, 2016). Furthermore, ice-
444 marginal lake formation can destabilise and perturb wider ice-margin dynamics through the initiation
445 of a positive feedback whereby enhanced rates of mass loss increase local ice-surface gradients, thus
446 promoting acceleration, thinning and fracture of the ice-margin, which in turn creates favourable

447 conditions for amplified calving losses (Benn et al., 2007; Carrivick and Tweed, 2013). This feedback
448 has been invoked as the cause of the rapid ice-margin recession observed at an increasing number of
449 alpine glaciers (Naruse and Skvarca, 2000; Boyce et al., 2007; Basnett et al., 2013; Trussel et al., 2013;
450 King et al., 2018; Liu et al., 2020).

451

452 The correlations between rate of ice-margin change and lake area and intersect length respectively
453 (Figure 6c-d, Table 5), suggest that lake size exerts a control on rates of mass loss at lacustrine margins.
454 Although the augmented rates of ice-margin recession at larger lakes can be hypothesised to arise
455 from the combined effects of calving and subaqueous melt occurring over a greater length of the ice-
456 margin, it is likely that the greater water depths typically associated with larger lakes (e.g. Huggel et
457 al., 2002; Cook and Quincey, 2015) are also a key driver of ice-margin recession. In particular, several
458 empirical relationships have linked increased calving rates to greater lake depths (Warren et al., 1995;
459 Warren and Kirkbride, 2003), and accelerated rates of lacustrine ice-margin recession have been
460 observed following the retreat of termini into glacial overdeepenings (e.g. Kirkbride, 1993; Boyce et
461 al., 2007; Larsen et al., 2015). In addition, the increased buoyancy and reduced effective pressure
462 apparent at ice-margins terminating in deeper water favours the positive feedback between mass loss
463 and terminus recession.

464

465 Increases in lake area and depth could also explain the progressive growth in mean annual lacustrine
466 margin recession rates by an order of magnitude throughout the study, from 1.1 ma^{-1} between 1987
467 and 1992 to 11.5 ma^{-1} between 2010 and 2015 (Table 4, Figure 6e). A behavioural analysis of the lake
468 dataset in Carrivick and Quincey (2014) revealed that $\sim 45\%$ of all ice-marginal lakes in south-west
469 Greenland formed or increased in size between 1987 and 2010, in contrast to only $\sim 30\%$ of lakes
470 decreasing in size or draining over the same period. Furthermore, the inverse bed slope along much
471 of the ice sheet margin in south-west Greenland creates favourable conditions for ongoing lake
472 expansion in response to ice-margin recession (Carrivick et al., 2017a; Morlighem et al., 2017). Lake

473 persistence was the only independent variable in the LMMs that did not significantly correlate with
474 the rate of ice-margin change at lacustrine termini (Table 5), which may be indicative of a multifaceted
475 relationship between ice-margin recession and lake stability. For example, although the most
476 persistent lakes may be associated with greater rates of ice-margin recession due to their extended
477 prevalence, lakes in contact with rapidly retreating ice-margins may also be inherently less stable due
478 to increased opportunities for lake drainage through failure of the ice-dam or rapid changes to lake
479 morphometry (e.g. Russell et al., 2011; Carrivick et al., 2017b; Carrivick and Tweed, 2019).

480

481 An additional cause of the enhanced rates of recession at lacustrine margins observed over the
482 duration of this survey could be the lengthening of the season over which lacustrine processes,
483 including subaqueous melt and calving, were able to promote mass loss. For example, analyses of non
484 ice-contact lakes in the Arctic have identified an earlier break-up of winter ice-cover and an increase
485 in ice-free days in response to atmospheric warming over recent decades (Duguay et al., 2006;
486 Smejkalova et al., 2016; Surdu et al., 2016). Similar changes to the ice-cover regimes of ice-marginal
487 lakes in south-west Greenland could therefore have amplified ice-margin recession through the
488 prolonged operation of lacustrine processes associated with higher rates of mass loss, such as melt-
489 undercutting (e.g. Mallalieu et al., 2020). These processes are likely to be further accentuated in lakes
490 with a reduced duration of ice-cover by enhanced lake temperatures arising from the low albedo of
491 open water. Notably, the mean annual lacustrine margin recession rates measured in this study
492 increased following the switch to a negative phase of the North Atlantic Oscillation in the mid-1990s
493 (Table 4), which is typically associated with enhanced summertime warming in west Greenland (Hanna
494 et al., 2008; Bevis et al., 2019). In addition, further evidence of climatic control on rates of lacustrine
495 margin recession is provided by the significant positive correlations between ice-margin change and
496 latitude and altitude respectively (Figure 6a-b, Table 5), which highlight a strong association between
497 high rates of lacustrine recession and the warmer climatic conditions typically associated with lower
498 latitudes and altitudes. Consequently, the relationships identified here between latitude, altitude and

499 rates of lacustrine margin change, could be considered as tentative indicators of the future response
500 of lacustrine margins to anticipated increases in atmospheric forcing in western Greenland (Bevis et
501 al., 2019).

502

503 4.3 IMPLICATIONS AND FUTURE RESEARCH

504 In addition to enhancing local rates of ice-margin recession, the presence of lakes at the margin of the
505 GrIS could have profound implications for wider ice sheet dynamics and stability. For example, Price
506 et al. (2008) demonstrated that dynamic changes at the margins of the GrIS can propagate dozens of
507 kilometres up-ice via longitudinal coupling. Therefore enhanced recession at lacustrine margins and
508 resultant increases in surface gradients have significant potential to amplify surface velocities and
509 promote dynamic thinning up-ice of the lacustrine termini, particularly where lakes are large and deep
510 relative to the thickness of the ice-margin. Similar responses to lake formation and growth have been
511 extensively documented in the Himalaya, where lacustrine terminating glaciers account for an
512 increasingly disproportionate share of regional mass loss (Basnett et al., 2013; King et al., 2018; Brun
513 et al., 2019; King et al., 2019). Currently 434 km (~9 %) of the ice sheet margin in south-west Greenland
514 terminates in a lacustrine setting, in contrast to 153 km (~3 %) in a marine setting (Table 3). However,
515 thinning at the margins of the ice-sheet (Krabill et al., 2004; Pritchard et al., 2009), coupled with
516 continued atmospheric warming (Pattyn et al., 2018; Bevis et al., 2019) and the recession of the ice-
517 margin over an inverse bed slope (Carrivick et al., 2017a; Morlighem et al., 2017), will create
518 favourable conditions for enhanced ice-marginal lake formation and growth in south-west Greenland
519 in coming decades. Additionally, over longer timescales, the recession of marine termini onto land
520 (e.g. Joughin et al., 2010; Nick et al. 2013) will further increase the potential for lake formation at the
521 ice sheet margin. Consequently, it can be hypothesised that ice-marginal lakes will play an increasingly
522 important role in rates and patterns of deglaciation in Greenland, and that continued lake expansion
523 will amplify future mass loss from the south-western margin of the GrIS. Furthermore, inadequate
524 consideration of the impacts of lacustrine forcing at the margin of the GrIS could lead to increasing

525 error in projections of the ice sheet’s response to climate change, and its contribution to sea level rise.
526 The inclusion and parameterisation of lake – ice-margin interactions in numerical ice sheet models is
527 therefore increasingly desirable (Carrivick et al., 2020).

528

529 A more advanced understanding of the impact of lacustrine forcing on the margin of the GrIS could be
530 developed by focusing future research efforts in three main areas. Firstly, sections of the ice-margin
531 susceptible to lake formation and growth could be determined through the development of
532 morphometric and dynamic criteria, similar to those employed to forecast ice-marginal lake formation
533 in the Himalaya (Reynolds, 2000; Quincey et al., 2007), particularly if integrated with recent high-
534 resolution mapping of GrIS bed topography (e.g. Morlighem et al., 2017). In addition, knowledge of
535 basal topography and ice thickness can facilitate predictions of lake area and depth, which are
536 significant controls on rates of recession at lacustrine margins (Figure 6c). Secondly, regional-scale
537 analyses of changes in velocity, structure and ice-surface elevation up-ice of the lacustrine termini of
538 the GrIS are necessary to determine the magnitude of the dynamic response of the ice-sheet to lake
539 formation and thus refine estimates of mass loss and sea level rise from lacustrine margins. This
540 objective, and the extent to which the observations and conclusions drawn from this study in south-
541 west Greenland may be applicable to the wider ice sheet, will be greatly facilitated by the recent
542 generation of the first Greenland-wide multi-sensor inventory of ice-marginal lakes in How et al.
543 (2021). Finally, local-scale analyses of lacustrine ice-margin dynamics are required to improve
544 knowledge of the mechanisms driving enhanced ice-margin recession. In particular, calving processes
545 and rates of subaqueous melt remain relatively poorly constrained at lacustrine ice-margins (Haresign
546 and Warren, 2005; Trussel et al., 2013; Purdie et al., 2016; Truffer and Motyka, 2016; Mallalieu et al.,
547 2020).

548

549 **5. CONCLUSIONS**

550 This study has presented the first systematic analysis of changes in the extent of the terrestrial,
551 lacustrine and marine margins of the GrIS in south-west Greenland between 1987 and 2015. The
552 analysis revealed an extended and accelerating phase of ice-margin recession in south-west Greenland
553 from 1992 onwards, irrespective of ice-margin type. However, significant differences in rates of ice-
554 margin change also indicated a heterogeneous response at the respective ice-marginal environments
555 of the GrIS to comparable climatic forcing over the survey duration. Marine terminating ice-margins
556 exhibited the greatest magnitude and variability in ice-margin change, with rapid ice-margin recession
557 becoming pervasive from 1992. Mean ice-margin recession rates and variability in frontal behaviour
558 were also consistently greater at lacustrine termini than their terrestrial counterparts. In addition,
559 mean ice-margin recession rates at lacustrine termini increased by an order of magnitude over the
560 duration of the survey and progressively outpaced those measured at terrestrial ice-margins. This
561 study has also identified significant correlations between rates of lacustrine ice-margin recession and
562 lake parameters, including lake area, latitude, altitude and the length of the lake – ice-margin
563 interface. The progressive increase in rates of lacustrine ice-margin recession measured over the
564 duration of the survey are theorised to have arisen from increases in lake size and a lengthening of
565 the season in which calving and subaqueous melt processes can promote mass loss at lacustrine
566 termini. These results suggest that ice-marginal lakes have become increasingly significant drivers of
567 ice-margin recession and thus mass loss at the GrIS, and are likely to further increase in importance in
568 response to enhanced ice-marginal lake prevalence in coming decades. Further research is therefore
569 necessary to better parameterise the causal connections between ice-marginal lake evolution and
570 enhanced ice-margin recession in Greenland, and thus refine the contribution of mass loss from the
571 lacustrine margins of the GrIS to sea level rise projections.

572

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578

579 **DATA STATEMENT**

580 The dataset of ice-margin change used in this analysis is available from the UK Polar Data Centre:
581 <https://doi.org/...> The R code for the statistical analyses is available from GitHub: <https://doi.org/...>
582 (*DOIs will be confirmed prior to publication*).

583

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