

Supplementary material for “Gulf of Alaska ice-marginal lake area change over the Landsat record and potential physical controls”

Hannah R. Field^{1,2}, William H. Armstrong¹, and Matthias Huss^{3,4,5}

¹Department of Geological and Environmental Sciences, Appalachian State University, Boone, NC 28607,
USA

²School of Earth Sciences, The Ohio State University, Columbus, OH 43210, USA

³Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Zurich, 8093, Switzerland

⁴Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland

⁵Department of Geosciences, University of Fribourg, Fribourg, Switzerland

Correspondence to: armstrongwh@appstate.edu

Table of contents

This supplement contains the following materials:

- Figures S1 – S10

- Tables S1 – S4. Tables S1 and S3 are very large and difficult to display on a single page. These tables are provided as comma separated values files in the supplemental online material.

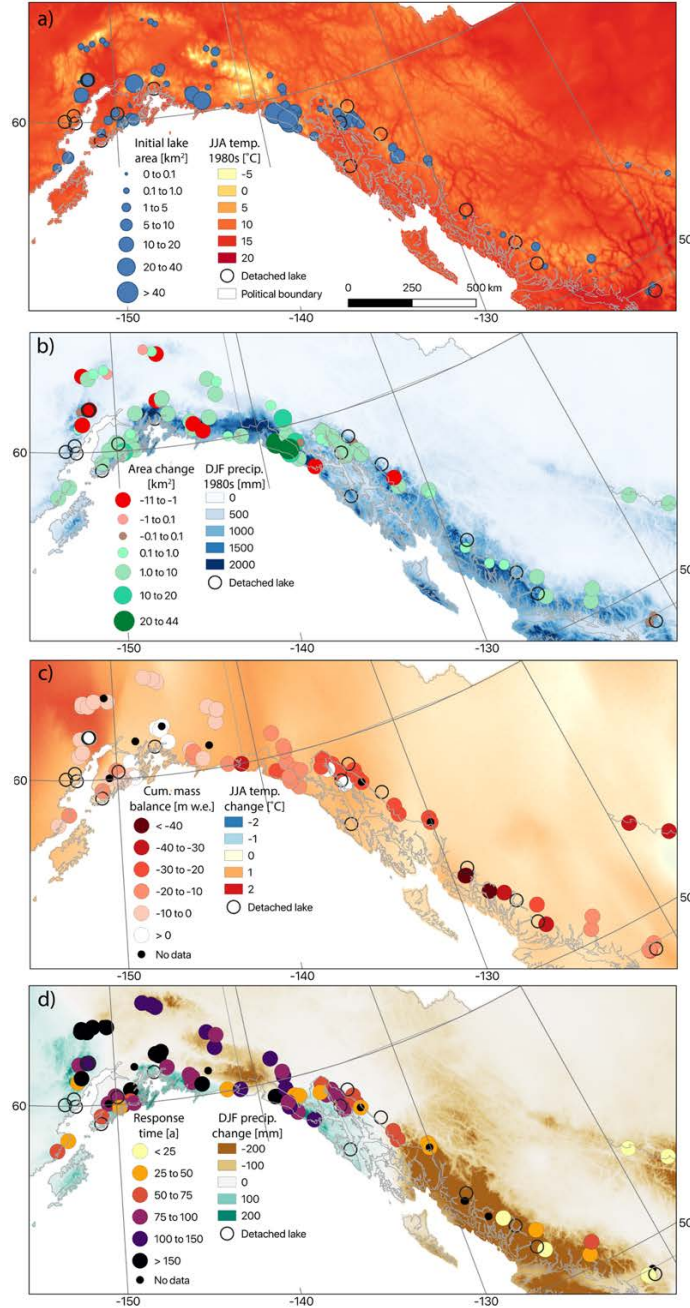
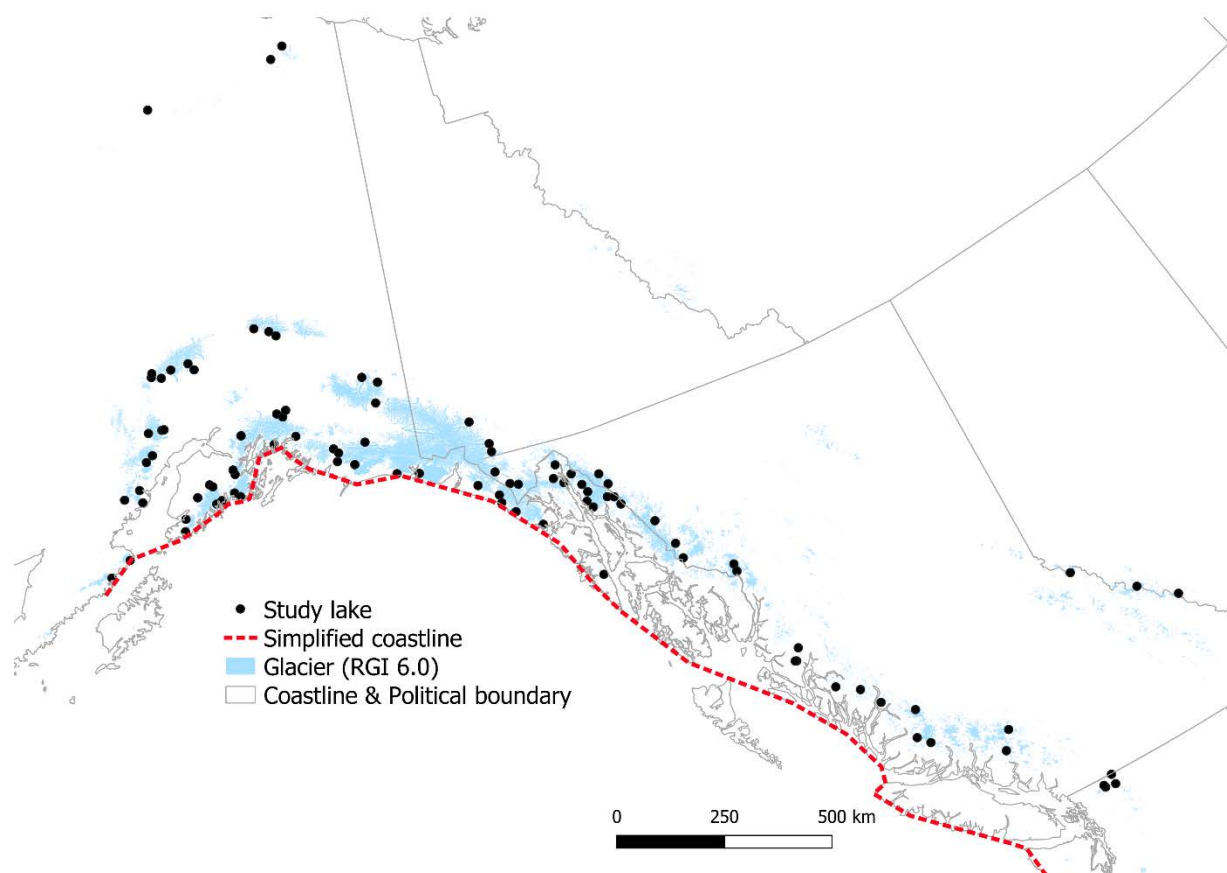


Figure S1: Map-view of select climatological and glaciological variables investigated in this study, along with ice-marginal lake attributes. (a) Reanalysis summer (June, July, August) air temperature averaged over 1980-1989 (raster data) and lake area at the start of the study period (point data). Lakes that detached from their associated glacier during the study period are shown as unfilled circles. Political boundaries are shown as gray lines. (b) Reanalysis winter (December, January, February) precipitation totals averaged over 1980-1989 (raster data), along with ice-marginal lake area change over the study period (point data). (c) Change in summer air temperature averages between the 2000-2009 decade and the 1960-1969 decade (raster data). Modeled mass balance of each lake-associated glacier, cumulated over 1980-2016 (point data). (d) Change in winter precipitation totals averaged between 2000-2009 and 1960-1969 (raster data). Estimated time required for glaciers to equilibrate with a step change in climate for all lake-associated glaciers (point data). Climate reanalysis data are from Scenarios Network for Alaska + Arctic Planning (SNAP), accessible at <http://ckan.snap.uaf.edu/dataset>.



1065 **Figure S2. Illustration of simplified coastline (dashed red line) used for measuring a study lake's (black dots) distance to the open ocean. The length of the shortest line between a lake and the simplified coastline was measured manually.**

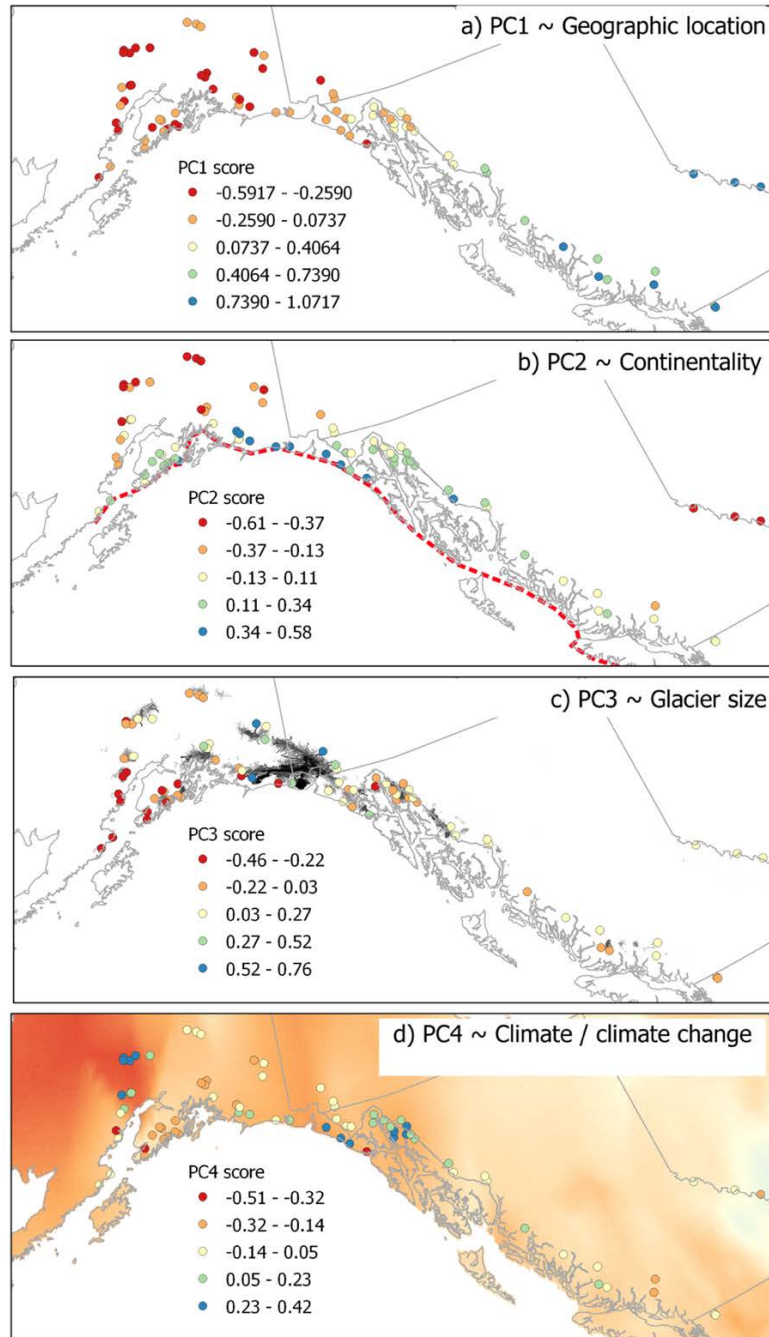


Figure S3. Map-view distribution of principal components scores for PC axes 1 – 4. We provide our physical interpretations for each axis in the upper right of each panel, with greater support provided in Sec 4.5 and Table S2. (a) PC1 scores, which vary systematically from northwest to southeast, and we interpret to primarily reflect a lake’s geographic position. (b) PC2 scores, which vary systematically from distance to the open ocean (dashed red line), interpreted to reflect continentality. (c) PC3 scores, the axis that loads strongly with glaciological attributes (Table S2). Background image shows glaciers (RGI 6.0), where dark colors indicate glaciers with large area. (d) PC4 scores, the axis which loads strongly with climatic variables. Background image shows summer temperature change between 1960 – 1969 and 2000 – 2009, with red colors indicating regions with greater summer temperature increase. A quantitative scale for this background image is shown in Fig. S1c.

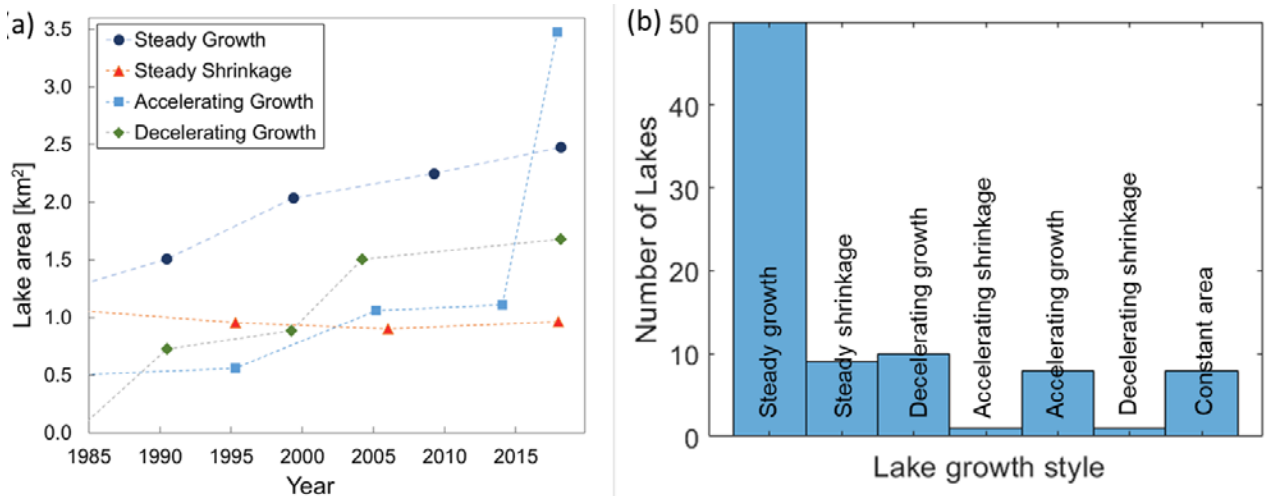


Figure S4: (a) Example of lake area timeseries of lakes exhibiting varied lake area change behaviors and (b) distribution of area change styles of study lakes.

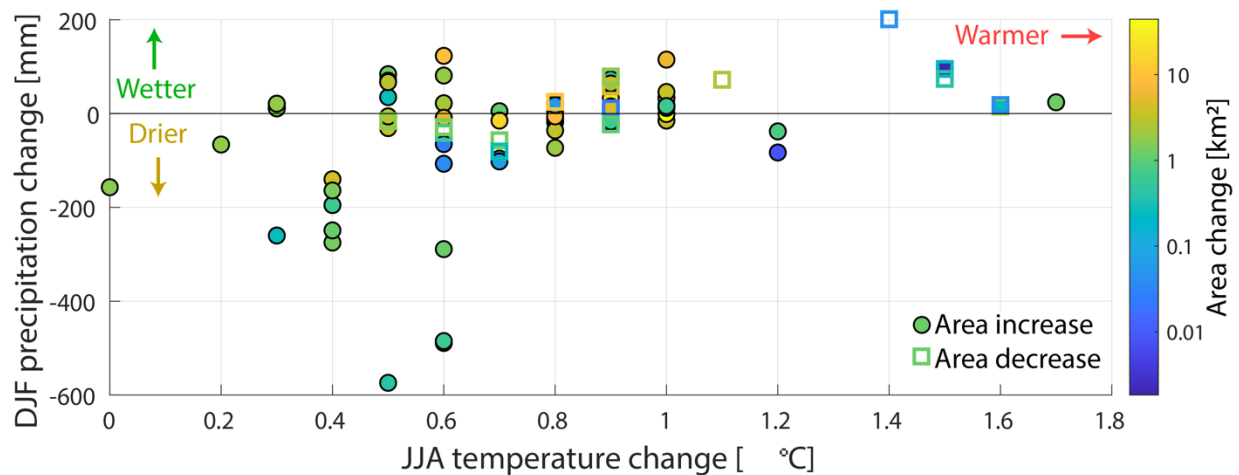


Figure S5. Changes in glacier mass-balance relevant climatic variables and absolute ice-marginal lake area change (colors). Climatic changes are computed as the difference between the 2000-2009 decadal average and the 1960-1969 decadal average, as estimated by the SNAP climate reanalysis dataset. Filled circles correspond to lakes with increasing area, whereas empty squares denote lakes with decreasing area. The greatest lake area change occurs in regions with near-zero (or slightly positive) winter precipitation change and moderate summer warming, suggesting that lake area change is not closely tied to changing climatic factors that decrease glacier mass balance.

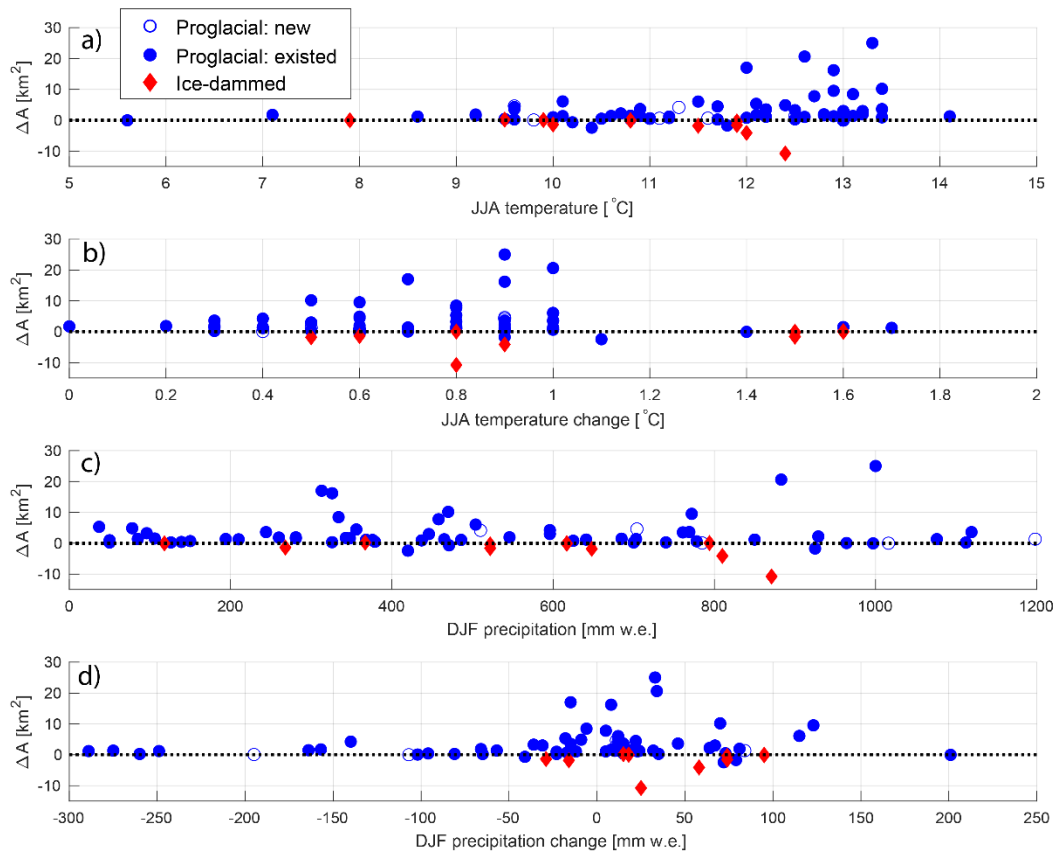


Figure S6. Absolute area change and climate variables for proglacial (blue circle) and ice-dammed (red diamond) lakes. (a) Summer temperature at each lake for the 2000 – 2009 decade. (b) Change in summer air temperature at each lake between 2000 – 2009 and 1960 – 1969. A positive change indicates warmer temperatures in recent times. (c) Winter precipitation at each lake for the 2009 – 2009 decade. (d) Change in winter precipitation at each lake between 2000 – 2009 and 1960 – 1969. A positive change indicates warmer temperatures in recent times. A positive change indicates wetter winters in recent times.

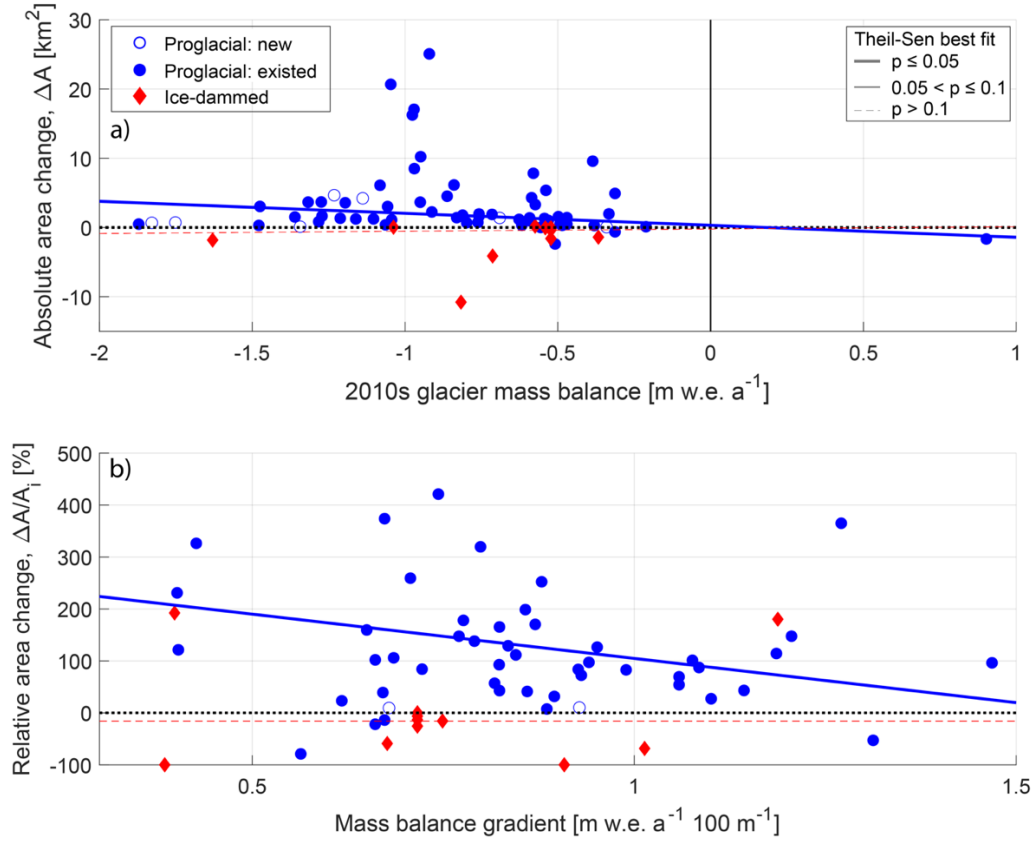
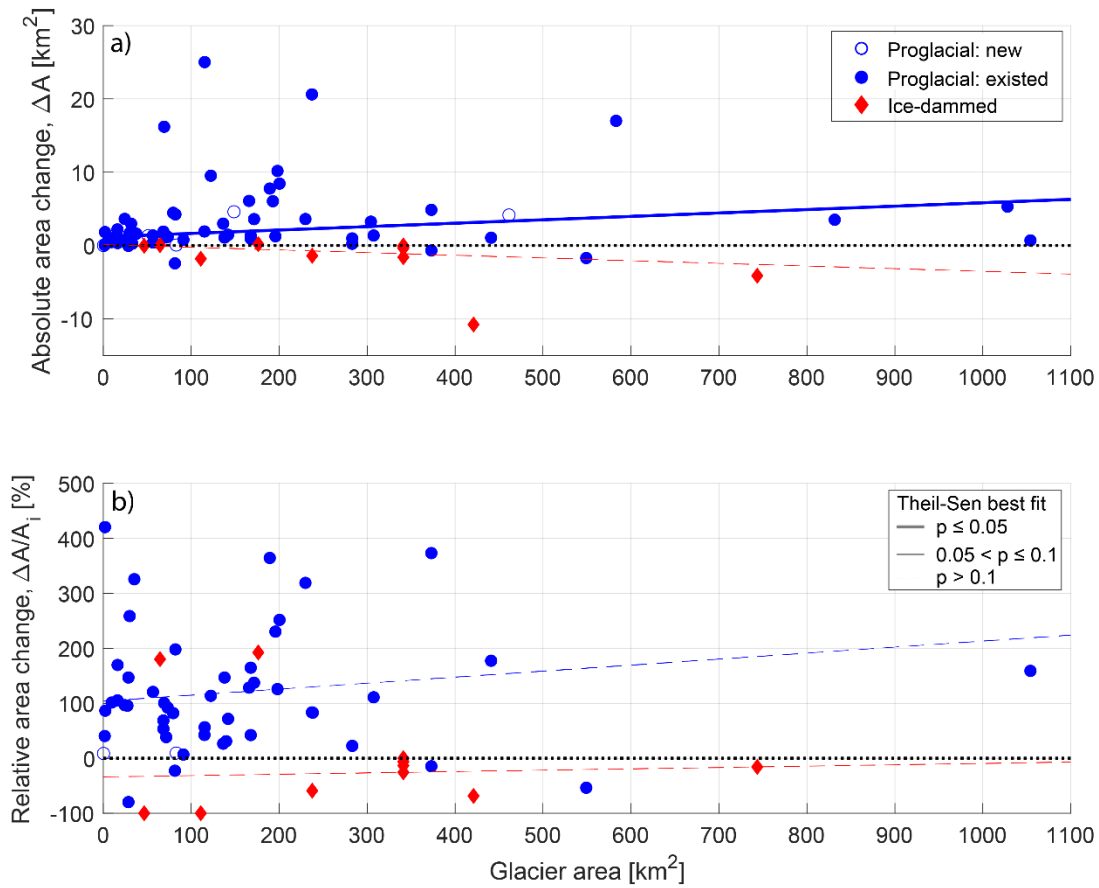


Figure S7. The relationship between (a) absolute lake area change and modeled glacier balance over 2010 – 2016, and (b) relative ice-marginal lake area change and modeled glacier mass balance gradient. Proglacial lakes are indicated by blue circles and ice-dammed lakes as red diamonds. On both panels, lines show the linear fit to proglacial (blue) and ice-dammed (red) lakes as estimated to by the non-parametric Theil-Sen robust line. Thick solid lines show relationships that are significant at the $p \leq 0.05$ level, thin solid lines show $0.05 < p \leq 0.1$ relationships, and thin dashed lines show $p > 0.1$ relationships. All significance values are estimated by the Kendall rank correlation test. The black dotted line shows zero lake area change. Unfilled symbols indicate lakes that appeared during the study period. The vertical black line in a) indicates a zero glacier-wide-average mass balance, indicating a glacier in equilibrium with climate. a) shows that proglacial lakes downstream from glaciers with more negative mass balance are growing fastest in terms of absolute lake area. b) shows that proglacial lakes downstream from glaciers with “flat” mass balance gradients, characteristic of continental glaciers, are growing more rapidly in terms of relative area change.



1115 **Figure S8. The relationship between lake-associated glacier area and (a) absolute and (b) relative lake area change for**
proglacial (blue circle) and ice-dammed (red diamond) lakes. On both panels, lines show the linear fit to proglacial (blue)
and ice-dammed (red) lakes as estimated to by the non-parametric Theil-Sen robust line. Thick solid lines show
relationships that are significant at the $p \leq 0.05$ level, thin solid lines show $0.05 < p \leq 0.1$ relationships, and thin dashed lines
show $p > 0.1$ relationships. All significance values are estimated by the Kendall rank correlation test. The black dotted line
1120 **shows zero lake area change. Unfilled symbols indicate lakes that appeared during the study period. a) shows that, in terms**
of absolute lake area, proglacial lakes downstream from larger glaciers are growing faster than those downstream from
small glaciers.

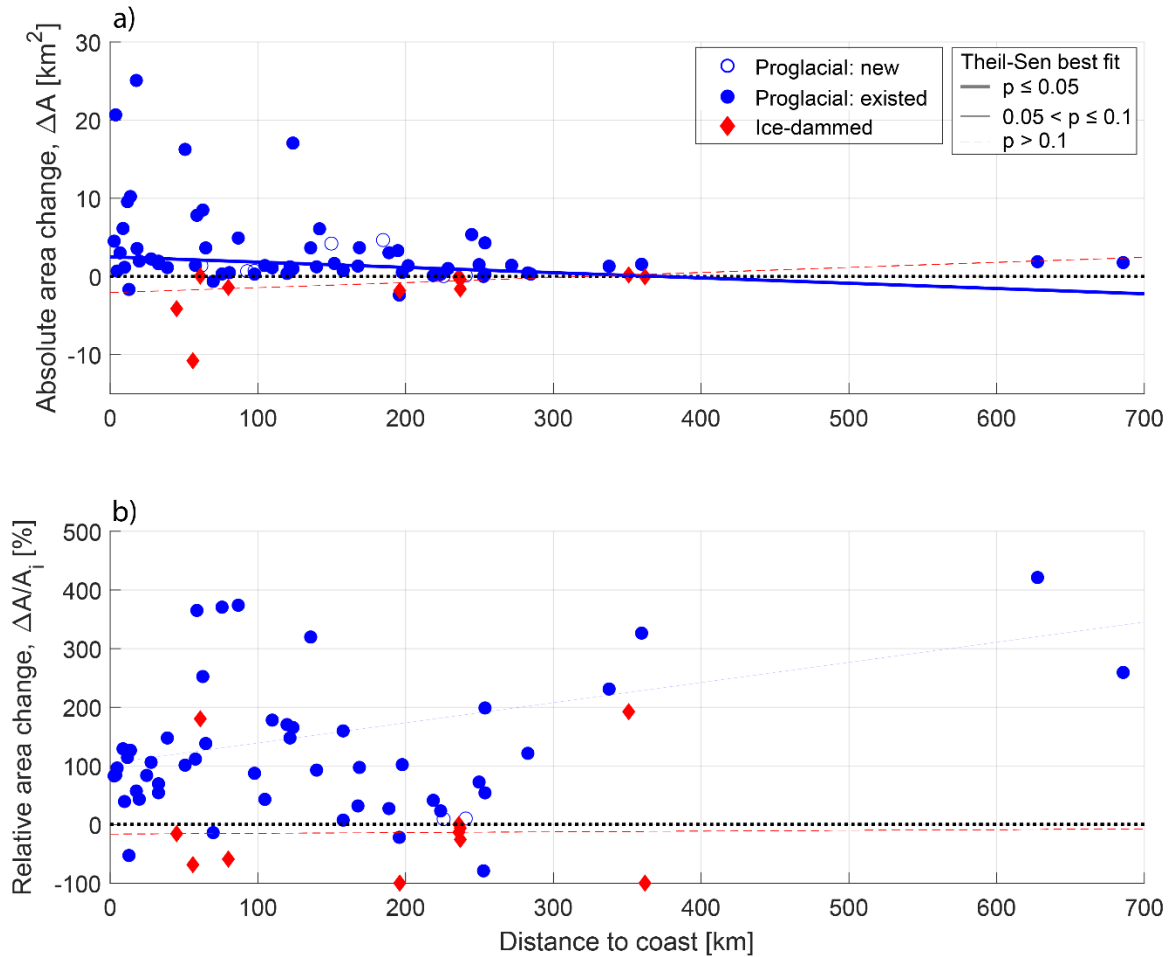


Figure S9. The relationship between an ice-marginal lake's distance from the open ocean and (a) absolute and (b) relative lake area change for proglacial (blue circle) and ice-dammed (red diamond) lakes. On both panels, lines show the linear fit to proglacial (blue) and ice-dammed (red) lakes as estimated to by the non-parametric Theil-Sen robust line. Thick solid lines show relationships that are significant at the $p \leq 0.05$ level, thin solid lines show $0.05 < p \leq 0.1$ relationships, and thin dashed lines show $p > 0.1$ relationships. All significance values are estimated by the Kendall rank correlation test. The black dotted line shows zero lake area change. Unfilled symbols indicate lakes that appeared during the study period. a) shows that coastal lakes are growing faster in terms of absolute area, but interior lakes are growing faster in terms of relative area change.

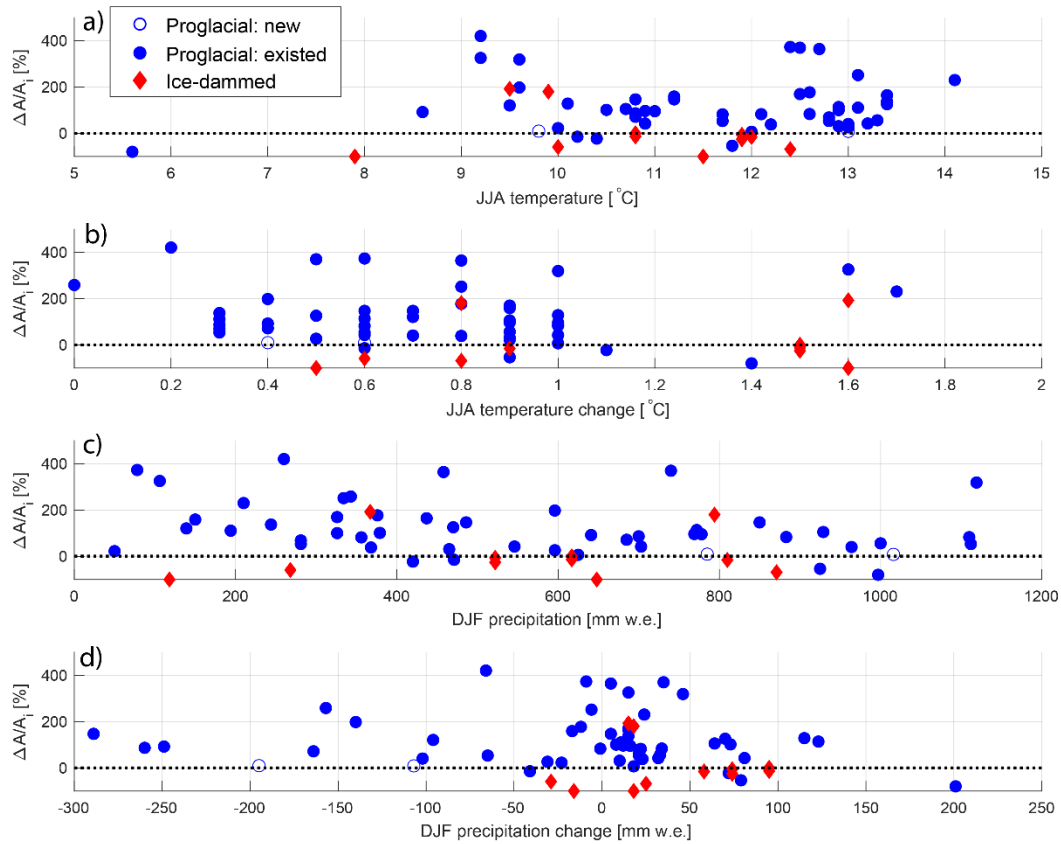


Figure S10. Relative area change and climate variables for proglacial (blue circle) and ice-dammed (red diamond) lakes. (a) Summer temperature at each lake for the 2000 – 2009 decade. (b) Change in summer air temperature at each lake between 2000 – 2009 and 1960 – 1969. A positive change indicates warmer temperatures in recent times. (c) Winter precipitation at each lake for the 2009 – 2009 decade. (d) Change in winter precipitation at each lake between 2000 – 2009 and 1960 – 1969. A positive change indicates wetter winters in recent times. A positive change indicates wetter winters in recent times.

Supplementary Table 1. Excel spreadsheet with lake area time series and area change, as well as extracted climatic, glaciologic, and geometric variables for all study lakes. This file is provided as a separate Excel spreadsheet.

1150

Supplementary Table 2. Results of principal components analysis. The leftmost columns show environmental variables, where the rightmost columns show input variable loadings onto each principal component (PC) axis. The second row shows percent variance in the input variables (after standardization) explained by each principal component axis. High absolute value loadings indicate a variable that is important in setting that PC axis score. Positive (negative) loadings indicate that a large positive (negative) value of the input variable is associated with a large positive (negative) score for that PC axis. The variance explained decreases in a quasi-exponential fashion with increasing PC axis number. Variable loadings with absolute values greater than 0.25 appear bolded and in red font. PC5 duplicates many of the strong loadings as PC4. Given this fact, and that explained variance declines for the following PC axes, we discard the remaining PC axes from further analysis. However, we do display variable loadings for PCs 5-8 here in gray text.

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PC axis number		1	2	3	4	5	6	7	8
Variance explained (%)		35.2	18.2	12.1	7.8	6.4	4.4	3.8	3.0
Climatological	JJA Temperature	-0.13	0.28	-0.04	-0.28	-0.29	-0.29	-0.11	-0.17
	JJA Temp. Change	-0.26	-0.04	0.00	0.63	0.18	0.01	-0.44	-0.09
	DJF Precipitation	0.15	0.32	0.00	0.29	0.62	-0.05	0.08	0.25
	DJF Precip. Change	-0.23	0.05	-0.11	0.07	0.08	-0.04	0.02	0.02
	Distance from coast	0.12	-0.33	0.09	0.13	-0.11	-0.19	-0.13	-0.13
Glaciological	Glacier area	-0.24	0.09	0.62	-0.11	-0.14	-0.08	-0.21	0.59
	Glacier width	-0.13	0.12	0.23	0.04	0.04	-0.33	0.31	0.19
	Lake adjacent median ice thickness	-0.39	0.01	0.53	-0.01	0.11	0.31	0.09	-0.55
	Mass balance gradient	0.15	0.56	0.02	-0.28	0.18	0.45	-0.10	-0.07
	2010s average annual mass balance	-0.15	-0.18	-0.03	-0.35	0.43	-0.33	-0.27	-0.11
	1980-2016 cumulative annual mass balance	-0.24	-0.11	-0.08	-0.36	0.37	-0.19	-0.13	-0.08
Topographic	Latitude	-0.36	-0.08	-0.06	0.09	-0.11	0.24	0.13	0.04
	Longitude	0.55	0.10	0.41	0.10	-0.04	-0.21	-0.28	-0.30
	Elevation	0.27	-0.52	0.26	-0.16	0.27	0.24	0.29	0.11
	Initial lake area	-0.05	0.20	0.10	0.17	0.06	-0.39	0.58	-0.26

Supplementary Table 3. Results from Kendall correlation tests between each variable investigated in this study and lake area change of all ice-marginal lakes (proglacial and ice-dammed). The correlation coefficient (τ) and p-value are shown for each statistical test. Red boxes indicate relationships that are significant at the $p \leq 0.05$ level, while yellow boxes show relationships with $0.05 < p \leq 0.1$. This file is provided as a separate Excel spreadsheet.

index	Parameter	Absolute area change				Relative area change			
		Proglacial		Ice-dammed		Proglacial		Ice-dammed	
		τ	p	τ	p	τ	p	τ	p
1	'lake_area_change'	N/A	N/A	N/A	N/A	0.14	0.07	0.56	0.00
2	'long'	-0.06	0.47	-0.16	0.45	0.05	0.53	0.01	1.00
3	'lat'	0.03	0.74	0.23	0.28	0.13	0.10	0.01	1.00
4	'elevation_m'	-0.27	0.00	0.30	0.15	0.19	0.02	0.12	0.58
5	'temp_jja_1960s_degC'	0.17	0.03	-0.26	0.23	-0.14	0.09	-0.12	0.58
6	'temp_jja_1980s_degC'	0.20	0.01	-0.20	0.35	-0.14	0.09	-0.07	0.78
7	'temp_jja_2000s_degC'	0.19	0.02	-0.20	0.35	-0.13	0.10	-0.07	0.78
8	'tempChange_jja_2000s-1960s_degC'	0.04	0.63	0.09	0.70	0.00	0.99	0.02	0.96
9	'precip_djf_1960s_mm'	-0.06	0.49	-0.46	0.03	-0.07	0.40	-0.06	0.83
10	'precip_djf_1960s_mm'	-0.02	0.79	-0.43	0.04	-0.09	0.28	-0.03	0.91
11	'precip_djf_1960s_mm'	-0.02	0.78	-0.46	0.03	-0.08	0.31	-0.06	0.83
12	'precip_djf_change_2000s-1960s_mm'	0.20	0.01	-0.11	0.62	-0.15	0.06	0.11	0.62
13	'Init_lake_area'	0.33	0.00	-0.41	0.05	-0.52	0.00	-0.05	0.83
14	'glacier_Area'	0.29	0.00	-0.38	0.11	-0.02	0.80	0.10	0.73
15	'Zmin'	-0.26	0.00	0.60	0.01	0.20	0.01	0.19	0.44
16	'Zmax'	0.07	0.43	0.13	0.62	0.01	0.93	0.16	0.53
17	'Zmed'	-0.07	0.41	0.32	0.18	0.07	0.42	0.22	0.36
18	'Slope'	-0.21	0.01	-0.02	1.00	0.05	0.56	-0.21	0.40
19	'Aspect'	0.08	0.35	0.03	0.94	-0.05	0.53	0.00	1.00
20	'Lmax'	0.27	0.00	-0.35	0.14	-0.05	0.58	-0.06	0.83
21	'glacierWid_m'	0.32	0.00	-0.18	0.46	-0.14	0.10	0.18	0.46
22	'valleyWid_m'	0.31	0.00	-0.30	0.20	-0.11	0.19	-0.06	0.84
23	'1980s_averageAnnualBalance_mwea'	0.00	0.99	-0.03	0.94	-0.08	0.37	0.06	0.83
24	'1990s_averageAnnualBalance_mwea'	-0.07	0.44	0.00	1.00	-0.06	0.48	0.10	0.73
25	'2000s_averageAnnualBalance_mwea'	-0.06	0.51	0.06	0.83	-0.06	0.51	0.16	0.53
26	'2010s_averageAnnualBalance_mwea'	-0.17	0.04	0.03	0.94	-0.10	0.22	0.00	1.00
27	'1980_2016_averageAnnualBalance_mwea'	-0.07	0.41	0.03	0.94	-0.07	0.40	0.13	0.62
28	'1980_2016_summedAnnualBalance_mwea'	-0.07	0.41	0.03	0.94	-0.07	0.40	0.13	0.62
29	'Area[km2]'	0.22	0.01	-0.38	0.11	0.08	0.37	0.10	0.73
30	'Volume[km3]'	0.20	0.02	-0.38	0.11	0.07	0.42	-0.03	0.94
31	'max_thick(m)'	0.18	0.04	-0.19	0.44	0.07	0.45	-0.03	0.94
32	'h_min'	-0.14	0.11	0.35	0.14	0.10	0.23	0.19	0.44
33	'h_max'	-0.08	0.36	0.16	0.53	0.19	0.03	0.13	0.62
34	'h_med'	-0.15	0.08	0.41	0.08	0.19	0.03	0.32	0.18
35	'slope_AVG'	-0.17	0.05	0.36	0.13	-0.01	0.87	-0.13	0.62
36	'b_tongue(mw.e.a-1)'	-0.09	0.28	0.22	0.36	-0.02	0.82	-0.13	0.62
37	'acc_win(mw.e.a-1)'	0.07	0.43	-0.64	0.01	-0.18	0.04	-0.16	0.53
38	'tau(year)'	0.12	0.18	0.16	0.53	0.13	0.15	0.00	1.00
39	'dBdz(mw.e./100m)'	0.14	0.11	-0.38	0.11	-0.18	0.04	0.10	0.73
42	'dBdz_acc(mw.e./100m)'	0.00	0.97	-0.29	0.23	0.08	0.37	0.02	1.00
43	'min_thickness_m'	0.18	0.05	0.29	0.29	0.03	0.71	0.47	0.07
44	'p25_thickness_m'	0.23	0.01	0.33	0.22	0.12	0.18	0.69	0.00
45	'median_thickness_m'	0.25	0.00	0.02	1.00	0.11	0.20	0.47	0.07
46	'mean_thickness_m'	0.24	0.01	0.02	1.00	0.10	0.24	0.38	0.16
47	'p75_thickness_m'	0.25	0.00	-0.02	1.00	0.09	0.30	0.42	0.11
48	'max_thickness_m'	0.24	0.01	-0.07	0.86	0.09	0.30	0.29	0.29
49	'iqr_thickness_m'	0.24	0.01	-0.38	0.16	0.05	0.60	0.16	0.60
50	'stdev_thickness_m'	0.24	0.01	-0.33	0.22	0.06	0.49	0.11	0.73
51	'dist_to_coast km'	-0.23	0.01	0.39	0.12	0.16	0.08	0.09	0.75

1170 **Supplementary Table 4.** Kendall tau correlation coefficients for significant ($p \leq 0.10$) bivariate correlations between climatic, geomorphic, and glaciologic variables investigated presented in Table 2. Bolded text indicate $p \leq 0.05$ relationships, while regular text indicates $0.05 < p \leq 0.1$ relationships.

	lat	lon	elev	initArea	coastDist	temp	dTemp	prcp	dPrpc	glArea	glWidth	hTerm	dbdz	b2010	bCum
lat	1.00	-0.59	-	-	-	-	0.31	-0.46	0.16	0.29	0.18	0.37	-0.42	0.40	0.53
lon	-0.59	1.00	0.16	-	0.15	-0.11	-0.16	0.31	-0.42	-0.17	-0.20	-0.19	0.28	-0.35	-0.53
elev	0.02	0.16	1.00	-0.38	0.41	-0.42	-	-	-0.35	-0.14	-0.28	-0.14	-0.21	0.12	-
initArea	-0.03	-	-0.38	1.00	-0.27	0.28	-	-	0.21	0.24	0.35	0.18	0.22	-	-
coastDist	0.10	0.15	0.41	-0.27	1.00	-0.36	0.18	-0.20	-0.29	-	-0.20	-	-0.39	-	-
temp	-0.01	-0.11	-0.42	0.28	-0.36	1.00	-0.14	-	0.16	0.17	0.24	-	0.19	-	0.15
dTemp	0.31	-0.16	-	-	0.18	-0.14	1.00	-	0.28	0.24	0.13	0.28	-0.23	-	0.15
prcp	-0.46	0.31	-	-	-0.20	-	-	1.00	-	-0.15	-	-0.15	0.37	-0.23	-0.24
dPrpc	0.16	-0.42	-0.35	0.21	-0.29	0.16	0.28	-	-	-	0.28	-	-	0.16	0.38
glArea	0.29	-0.17	-0.14	0.24	-	0.17	0.24	-0.15	-	-	0.44	0.67	-0.14	-	0.23
glWidth	0.18	-0.20	-0.28	0.35	-0.20	0.24	0.13	-	0.28	0.44	1.00	0.39	-	-	0.20
hTerm	0.37	-0.19	-0.14	0.18	-	-	0.28	-0.15	-	0.67	0.39	1.00	-	0.18	0.30
dbdz	-0.42	0.28	-0.21	0.22	-0.39	0.19	-0.23	0.37	-	-0.14	-	-	1.00	-0.30	-0.24
b2010	0.40	-0.35	0.12	-	-	-	-	-0.23	0.16	-	-	0.18	-0.30	1.00	0.63
bCum	0.53	-0.53	-	-	-	0.15	0.15	-0.24	0.38	0.23	0.20	0.30	-0.24	0.63	1.00