Dam type and ~~topological~~lake position ~~govern~~characterize ice-marginal lake area change in Alaska and NW Canada between 1984 and 2019

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1

Abstract. Ice-marginal lakes impact glacier mass balance, water resources, and ecosystem dynamics, and can produce catastrophic glacial lake outburst floods (GLOFs~~) via sudden drainage.~~). Multitemporal inventories of ice-marginal lakes are a critical first step in understanding the drivers of historic change, predicting future lake evolution, and assessing GLOF hazards. Here, we use Landsat-era satellite imagery and supervised classification to semi-automatically delineate lake outlines for four ~5-~~year time periods between 1984 and 2019 in Alaska and northwest Canada. Overall, ice-marginal lakes in the region have grown in total number (+~~176~~183 lakes, ~~36~~38% increase) and area (+~~467~~483 km^2, ~~57~~59% increase) between the time periods of 1984–1988 and 2016–2019~~. However, changes~~, though 56% of inventoried lakes did not experience detectable change. Changes in lake numbers and area were notably unsteady and nonuniform. We demonstrate that lake area changes are connected to dam type (moraine, bedrock, ice, or supraglacial) and ~~topological position~~the spatial relationship to their source glacier (proglacial, detached, unconnected, ice, or supraglacial), with important differences in lake behavior between the sub-groups. In strong contrast to all other dam types, ice-dammed lakes decreased in number (–~~6, 9,~~13% decrease) and area (–~~56~~51 km^2, ~~43~~40% decrease), while moraine-dammed lakes increased (+~~59, 28~~56, 26% and +~~468~~479 km^2, ~~85~~87% for number and area, respectively), a faster rate than the average when considering all dam types together. Proglacial lakes experienced the largest area changes and rate of change out of any ~~topological~~lake position throughout the period of study~~.~~, and moraine-dammed lakes which experienced the largest increases are associated with clean-ice glaciers (<19% debris cover). By tracking individual lakes through time and categorizing lakes by dam type, subregion, and ~~topological position~~location, we are able to ~~parse~~detect trends that would otherwise be ~~aliased~~obscured if these characteristics were not considered. This work highlights the importance of such lake characterization when performing ice-marginal lake inventories, and provides insight into the physical processes driving recent ice-marginal lake evolution.

1 Introduction

~~1.1 Ice-marginal lakes~~

Ice-marginal lakes are located adjacent to glaciers, commonly forming at glacier termini, tributary junctions, along glacier margins, or where glacially eroded bedrock or sediment creates topographic depressions (overdeepenings; Carrivick and Tweed, 2013; Cook and Quincey, 2015). These lakes can impact human societies in a multitude of ways, ranging from water resources (Immerzeel et al., 2020) and tourist attractions ~~(Wang and Zhou, 2019; Welling et al., 2020)~~(Wang and Zhou, 2019; Welling et al., 2020) to destructive and lethal hazards (Carrivick and Tweed, 2016; Cook et al., 2016; Emmer, 2017). Formation or drainage of lakes can impact ecosystem dynamics by providing or removing a source of stored freshwater, altering the sediment flux within a basin, creating new habitat (e.g., Milner et al., 2008), or altering downstream flow characteristics (Tweed and Carrivick, 2015; Jacquet et al., 2017). Glacial lake outburst floods (GLOFs; when a lake dam ~~suddenly~~ fails or is ~~breached~~overtopped; Clague and Evans, 2000) from ice-marginal lakes can have massive impacts on downstream river channel morphology and sediment supply (e.g., Jacquet et al., 2017), disrupt ecosystems (e.g., Meerhoff et al., 2018), destroy

2

40   infrastructure, and cause the loss of human lives (e.g., Carrivick and Tweed, 2016). Time-varying inventories of ice-marginal lakes are a critical first step in predicting future lake evolution and assessing GLOF hazards.
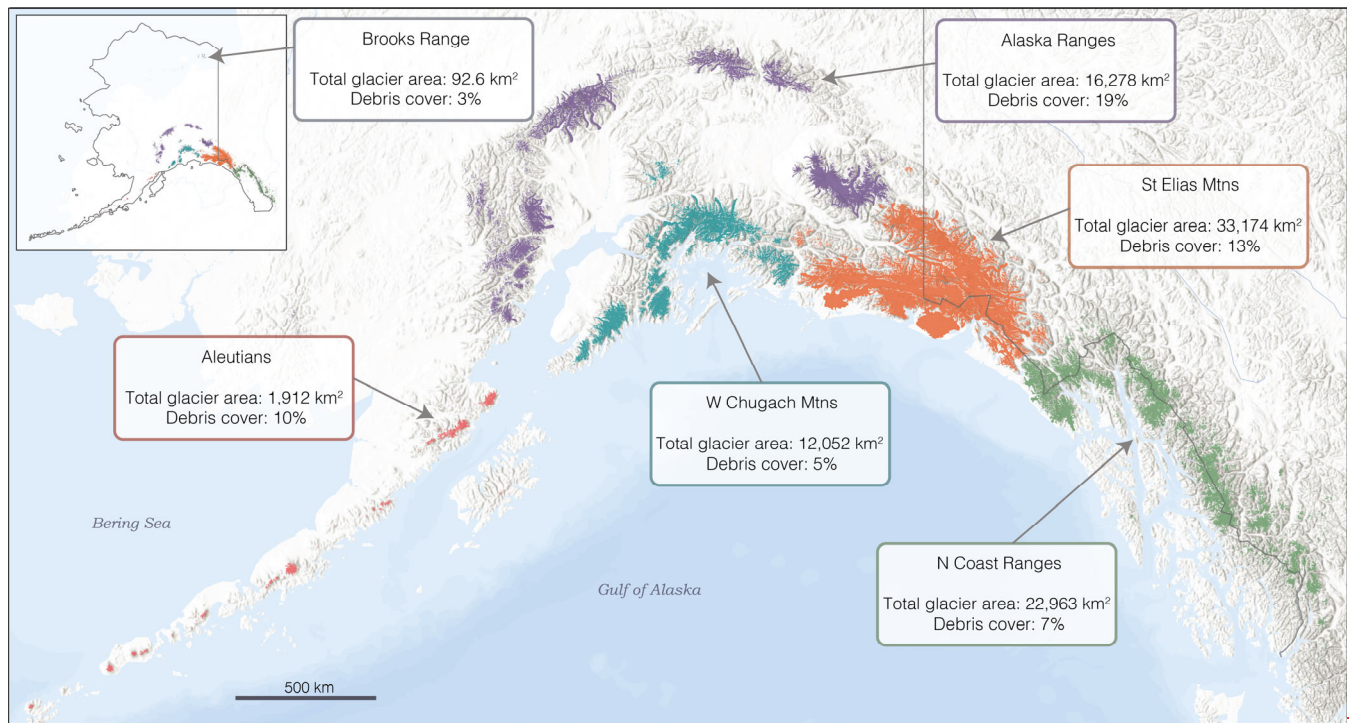
Global (Shugar et al., 2020) and regional ~~(Wang et al., 2013; Carrivick and Quincey, 2014; Nie et al., 2017; Song et al., 2017; Emmer et al., 2020) lake inventories document~~(Wang et al., 2013; Carrivick and Quincey, 2014; Glasser et al., 2016; Nie et al., 2017; Song et al., 2017; Emmer et al., 2020) lake inventories document recent increases in ice-marginal lakes, however,

45   many studies report solely on the change in total frequency and cumulative area of lakes within the study region, or consider only one type of lake (e.g., moraine-dammed or ice-dammed). ~~Disregarding~~By not accounting for individual lake characteristics and individual lake changes ~~could obscure~~through time, important trends could be aliased and ~~dynamics. If a limits the understanding of processes controlling area change. For example, if a~~ subset of lakes grow while ~~others~~other lakes drain, ~~reporting the overall lake frequency and area change underestimates total regional changes, as~~ the positive and negative

50   growth will offset one another~~.~~, and the overall lake frequency and area change would be small and therefore misleading. Alternatively, if a few large lakes dominate the documented area change for a region, ~~average~~applying the regionally-averaged lake growth to all lakes would ~~be overestimated~~overestimate growth, therefore preventing an accurate physical understanding of this change. In addition, the ecological consequences of lake changes may differ based on where ~~this~~lake growth occurs: a change from no lake to a 1 km^2 lake could have larger ecological and hazard implications than a large lake (e.g~~.~~., >10 km^2)

55   expanding by a few square kilometers (Dorava and Milner, 2000). Cumulative regional studies provide a first-order estimate of regional changes, however, individual lake change must be analyzed to develop a process-based understanding of area change in order to predict future lake growth and watershed-scale impacts~~, such as GLOF hazard potential~~.

Recent studies parse lakes by characteristics which ~~influence~~predict lake behavior, such as dam type and evolution phase (Emmer et al., 2015, 2020), or the spatial relationship to their source glacier (e.g., proglacial, supraglacial, unconnected,

60   detached; Nie et al., 2017; Rounce et al., 2017; Chen et al., 2021). In the Himalaya, proglacial lakes (located at the glacier terminus, in contact with ice) contributed to 83% of the total lake area increase from 1990 to 2015, while only composing 55% of the lake population (Nie et al., 2017). ~~Proglacial lakes enhance calving due to ice-water contact, resulting in lake expansion through terminus retreat (Carrivick and Tweed, 2013). In this same region, supraglacial lakes (located on debris-covered glacier surfaces) compose 3.5% of the population in 2015 and~~In this same region, supraglacial lakes (located on debris-covered

65   glacier surfaces) experienced the greatest percent increase in area (367%) since 1990, though they only constitute 1.2% of total lake area in 2015 (Nie et al., 2017). ~~Proglacial~~Himalayan proglacial lakes tend to be persistent and contribute the most to regional area growth, whereas supraglacial lakes are small and experience large spatio-temporal variation in area and location (Nie et al., 2017; Rounce et al., 2017; Chen et al., 2021). ~~In contrast, non-glacier-fed and unconnected glacier-fed lakes remained fairly stable or experienced small areal expansion (Nie et al., 2017).~~ In the Cordillera Blanca of Peru, many lakes

70   shifted from proglacial to detached (no longer in contact with ice) and the dominant dam type for proglacial lakes shifted from moraine-dammed in 1948 to bedrock-dammed in 2017 (Emmer et al., 2020). ~~This shift in dominant dam type was reflected in recent GLOF-producing lakes as well, as the most recent GLOFs originated from bedrock-dammed lakes (Emmer et al., 2020).~~

In both the Himalaya and the Cordillera Blanca, dam type and lake position help characterize lake behavior; this variability would be lost if only cumulative changes were reported. These studies support the inclusion of dam type and topological

75 position (used throughout to indicate spatial relationship of lakes to their source glacier) in comprehensive regional ice-marginal lake studies, suggesting that analyzing all lakes together masks patterns exhibited by each dam type, location, or subregion.

1.2 Aims of this study

Alaska's extensive glacier area (86,725 km²; second largest extent outside the ice sheets; Fig. 1; Farinotti et al., 2019; Zemp
80 et al., 2019), range of climates (maritime, transitional, continental, and Arctic; Miller et al., 1999), and varying glaciological characteristics (valleys, cirques, debris, icefields) allow for a unique abundance of ice dammed, supraglacial, and large proglacial lakes. The wide variety in ice marginal lake types, which likely respond differently to climate change (Field et al., 2021), makes this region particularly susceptible to aliasing of lake changes if considered all together. Although Alaska is sparsely populated, this region has experienced the largest number and highest frequency of recorded GLOFs globally,
85 accounting for 25% of all historical recorded events (Carrivick and Tweed, 2016). As one of the largest, yet understudied, glacierized mountain regions in the world, characterizing Alaska's ice marginal lakes and their evolution has important implications for local hazards (e.g., remote roads, the Trans Alaskan Pipeline), ecosystem dynamics, and comparable environments around the world.


90

4

Alaska's large glacier extent (86,723 km^2; second largest area outside the ice sheets; Fig. 1; Kienholz et al., 2015; Zemp et al., 2019) and recent retreat (Larsen et al., 2015) allow for the presence of many ice-marginal lakes, while a wide range of climate zones (maritime, transitional, continental, and Arctic; Miller et al., 1999), glacier morphologies (valleys, cirques, debris, icefields) and bedrock lithologies/surficial deposits (Wilson et al., 2015) lead to a variety of lake characteristics (e.g., dam type and topological position; Fig. 1). Two unique aspects of the Alaska region are the numerous large, low-elevation coastal lakes (e.g., Bear Glacier Lake, Malaspina Lake, Grand Plateau Glacier Lake), and that lakes tend to be larger than ice-marginal lakes found around the world (e.g., High Mountain Asia, Central Europe, and Alaska have median lake areas of 0.11 km^2, 0.11 km^2, and 0.17 km^2, respectively; Shugar et al., 2020). In addition, the lakes in this region are quite dynamic, as both the largest number and highest frequency of recorded GLOFs globally have occurred here, accounting for 25% of all recorded historical events (Carrivick and Tweed, 2016).

Previous studies of glacial lakes in Alaska ~~looked specifically at~~have examined ice-dammed lakes (Post and Mayo, 1971; Wolfe et al., 2014), a subset of ice-marginal lakes (Field et al., 2021)~~, individual case studies (e.g., Sturm and Benson, 1985; Anderson et al., 2003; Kienholz et al., 2020), or~~, individual case studies (e.g., Sturm and Benson, 1985; Anderson et al., 2003; Pelto et al., 2013; Kienholz et al., 2020), or as a regional subset within a global study (Shugar et al., 2020)~~, none of which comprehensively characterize regional trends. This is the first study to systematically inventory and characterize all ice-marginal lakes in Alaska using Landsat-era satellite imagery between 1984 and 2019. We aim to: (i) characterize ice-marginal lakes and~~. These studies are limited in their ability to comprehensively characterize regional trends for all lakes. Glaciers in this region are losing mass on the order of –75 Gt/yr (Larsen et al., 2015; Zemp et al., 2019), which represents the largest mass change and one of the highest specific mass changes for any region of the world. This change underscores the need for a time-varying lake inventory, given that ice-marginal lakes with different dam types and topological positions respond differently to glacier mass loss (e.g., Field et al., 2021).

The aims of the current study are to systematically inventory and characterize all ice-marginal lakes in Alaska using Landsat satellite imagery between 1984 and 2019. We aim to: (i) characterize ice-marginal lakes and decadal scale lake area change in Alaska; (ii) determine whether factors such as dam type, topological position, and region can ~~predict sign of~~characterize area change; and (iii) explore the interplay between the spatial distribution of lakes and regional characteristics such as glacier area, glacier complexity, and debris cover.
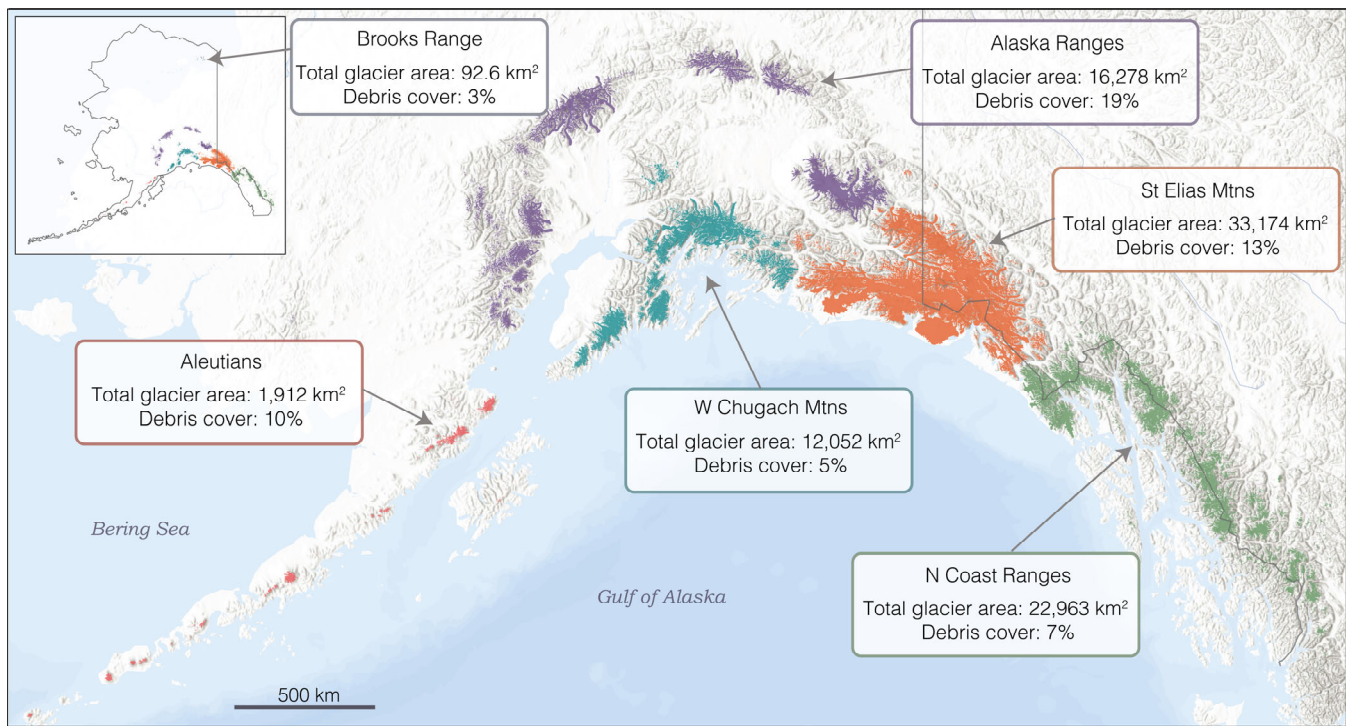
Figure 1: Distribution of glaciers as mapped by the Randolph Glacier Inventory (RGI Consortium, 2017) and subregions used to separate glaciated areas in Alaska and NW Canada (basemap provided by ESRI, 2021). Total glacier area (km²) and percent debris cover (percent of glacier surface covered by debris; Herreid and Pellicciotti, 2020) are displayed for each subregion.

2 Data and methods

2.1 Imagery and datasets

Cloud-free mosaics were compiled in Google Earth Engine (GEE), an open source, web-based remote sensing platform. Landsat 5 Thematic Mapper (TM), Landsat 7 Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI) surface reflectance ~~tier~~Tier 1 images were used to create 5-year composites (Table 1). Intervals were selected based on available imagery and to capture average lake outlines for a five-year period within each decade (1980s to 2010s). Few images are available for the late 1980s to early 1990s, and therefore this time period was excluded. Imagery was limited to a 10 km buffer around the Randolph Glacier Inventory ~~(RGI v6.0, Region 01~~, with source imagery for glacier outlines mostly from 2004 to 2010 for Region 01 (RGI v6.0; RGI Consortium, 2017; ~~Wang et al., 2012; Zhang et al., 2018)~~Wang et al., 2012; Kienholz et al., 2015; Zhang et al., 2018). For each pixel within the region of interest, the mosaicking algorithm calculates the median value of all cloud-free pixels between July 1st and September 31st for each year within the given time period (Fig. S1). Five-year mosaics minimize the impact of frequent cloud cover in Alaska, which complicates region-wide assessments on shorter ~~time-scales~~timescales. In theory, 5-year composites allow for an average shoreline delineation, capturing longer term trends rather than seasonal variation. However, ice-dammed lakes are known to fill and drain on sub-annual (e.g., Lago

6

Cachet Dos; Jacquet et al., 2017) to annual (e.g., Hidden Creek Lake; Anderson et al., 2003) timescales, so a lake may be

140   characterized as persistent (present at every time step) even though it has undergone multiple fill/drain cycles between composites. Owing to this limitation, our focus here is on decadal changes in lake number and area, not sub-annual lake dynamics relevant for GLOF frequency.

Table 1: Dataset and the resolution of the dataset used for each time step.

Time interval	Dataset	Sensor	Resolution	# of images used
1984–1988	Landsat 5	ETM	30 m	683
1997–2001	Landsat 5 & 7	ETM/ETM+	30 m	1312
2007–2011	Landsat 5 & 7	ETM/ETM+	30 m	2630
2016–2019	Landsat 8	OLI	30 m	1754

145   ## 2.2 Generating lake inventories 1984–2019

Image composites were classified in ArcGIS Pro using an object-based supervised classification (Support Vector Machine; Figure 2). Manual training samples were selected for snow, ice, water, bedrock, supraglacial debris, and vegetation for each individual time step as snow, ice, and water can vary from year to year. To reduce false positives from mountain shadows, which have a similar spectral signal as water (Fig. S2S3), a slope threshold of 10° was implemented (Zhang et al., 2018; Shugar

150   et al., 2020; Chen et al., 2021). We used a digital elevation model (DEM) composed of the national elevation dataset (NED; 10 m resolution) and Worldview-derived DEMs (resampled to 10 m resolution; DEMs created by the Polar Geospatial Center from DigitalGlobe, Inc. imagery). A minimum area threshold of 0.05 km^2 (~7.555 pixels squared) excludes pixel-level noise and small lakes with minimal hydrological impact and GLOF potential (Carrivick and Quincey, 2014; How et al., 2021). Lakes with margins entirely outside a 1 km buffer from the RGI were eliminated to minimize the inclusion of lakes

155   disconnected from a glacial system (Shugar et al., 2020). Wet, supraglacial debris bands are often misclassified as lakes, likely due to the presence of supraglacial water and therefore similar spectral properties (Fig. S3S4). A length to area threshold of 0.3 was implemented to remove these long and thin features with non typicalatypical lake shape. For this study, any lake within 1 km of the RGI was considered an ice-marginal lake, acknowledging that some low-lying lakes (e.g., Vitus Lake) may have tidal influence. Lakes which are within 1 km of the RGI and unconnected from a glacial system are noted (Sect. 2.3.2)

160   and treated separately (Table 2).

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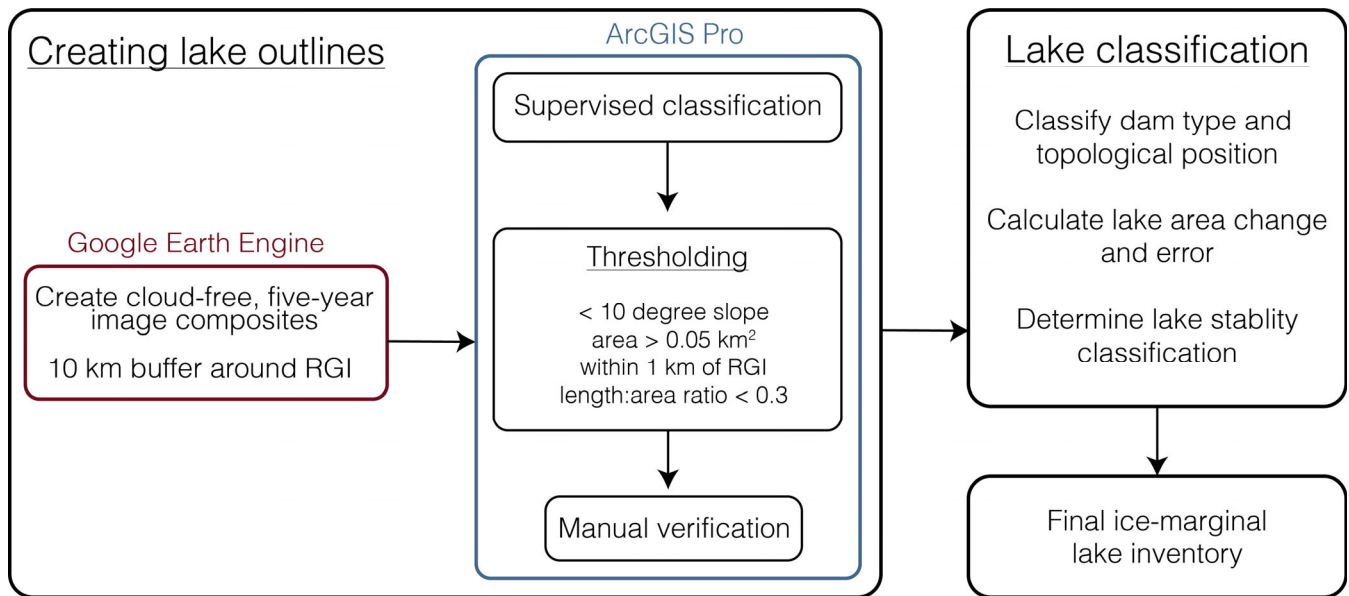
Figure 2: General workflow for creating the ice-marginal lake inventory for time periods 1984–1988, 1997–2001, 2007–2011, and 2016–2019.

All lake outlines were visually inspected and, if necessary, the lake margins were manually adjusted to produce a final

165   delineation. (Fig. S2). Lakes were added or excluded based on visual inspection and consideration of all four time steps together; lakes <0.05 km² were manually added back in if the lake grew in subsequent years to minimize false signals of lake formation. Lakes which coalesced or separated over time were given the same Lake ID to minimize misclassification of a lake forming or draining. Every lake in each time step was then classified by i) dam type (Sect. 2.3.1), ii) topological position (Sect. 2.3.2), and iii) stability (Sect. 2.3.3).

2.3 Lake characteristics

2.3.1 Dam type classification

Using a combination of DEMs and high-resolution satellite imagery (i.e., Maxar Technologies in Google Earth and ArcGIS basemap), each lake's dam type was visually interpreted and manually classified (Buckel et al., 2018). Four different dam types were identified in this study (Fig. 23):

175   *i) Moraine-dammed lakes:* most frequently located at the glacier terminus, impounded behind a terminal or lateral moraine (Otto, 2019);

ii) Ice-dammed lakes: located along glacier margins or within tributary valleys and blocked by glacier;

iii) Supraglacial lakes: found on the surface of the glacier, often dammed by glacier surface topography (ice or debris) within the ablation zone; and. For this study, we only observe supraglacial lakes within debris cover; and

180　*iv) Bedrock-dammed lakes:* frequently located in cirques with minimal remaining glacial ice, or in other overdeepenings created from glacial erosion (Otto, 2019).
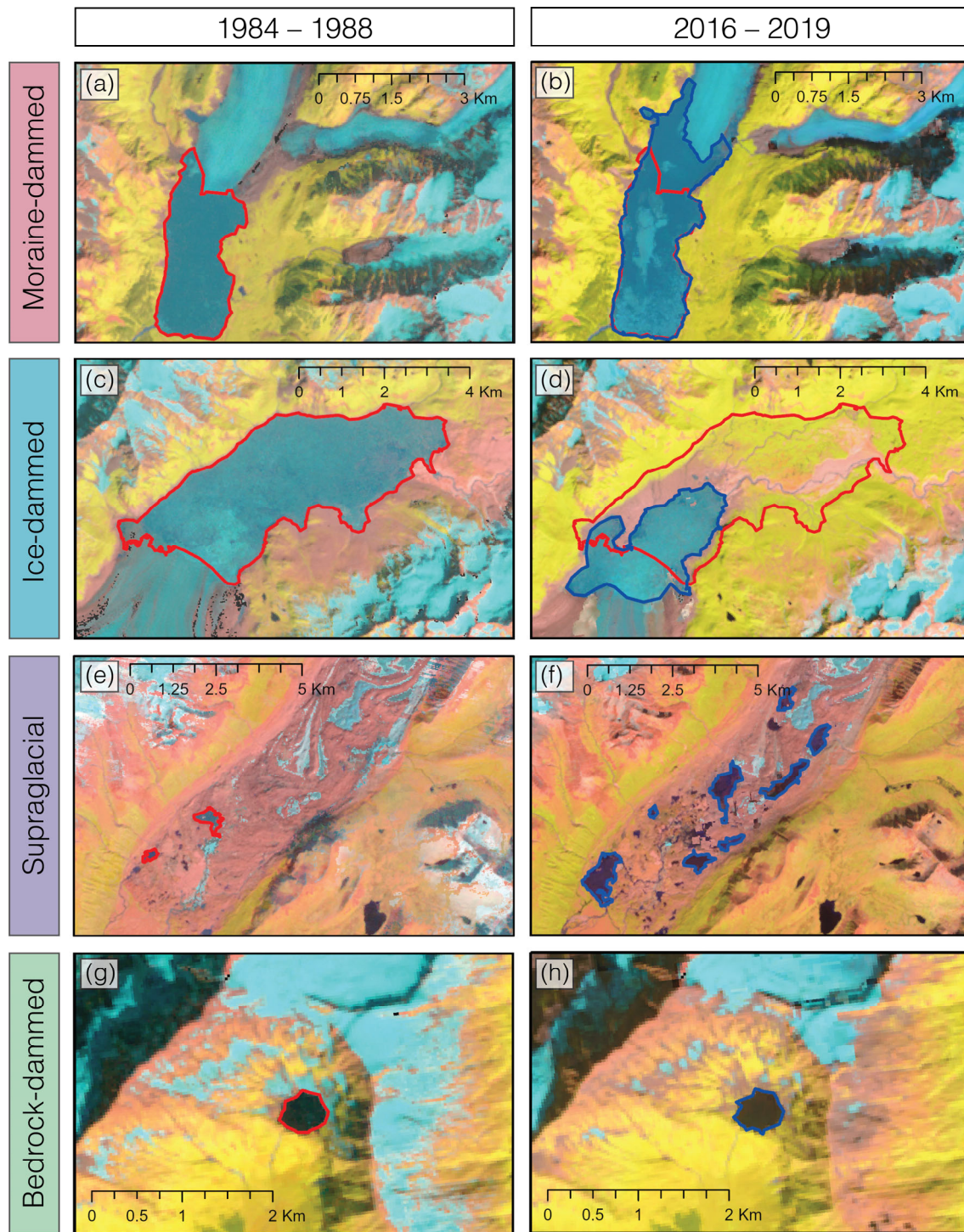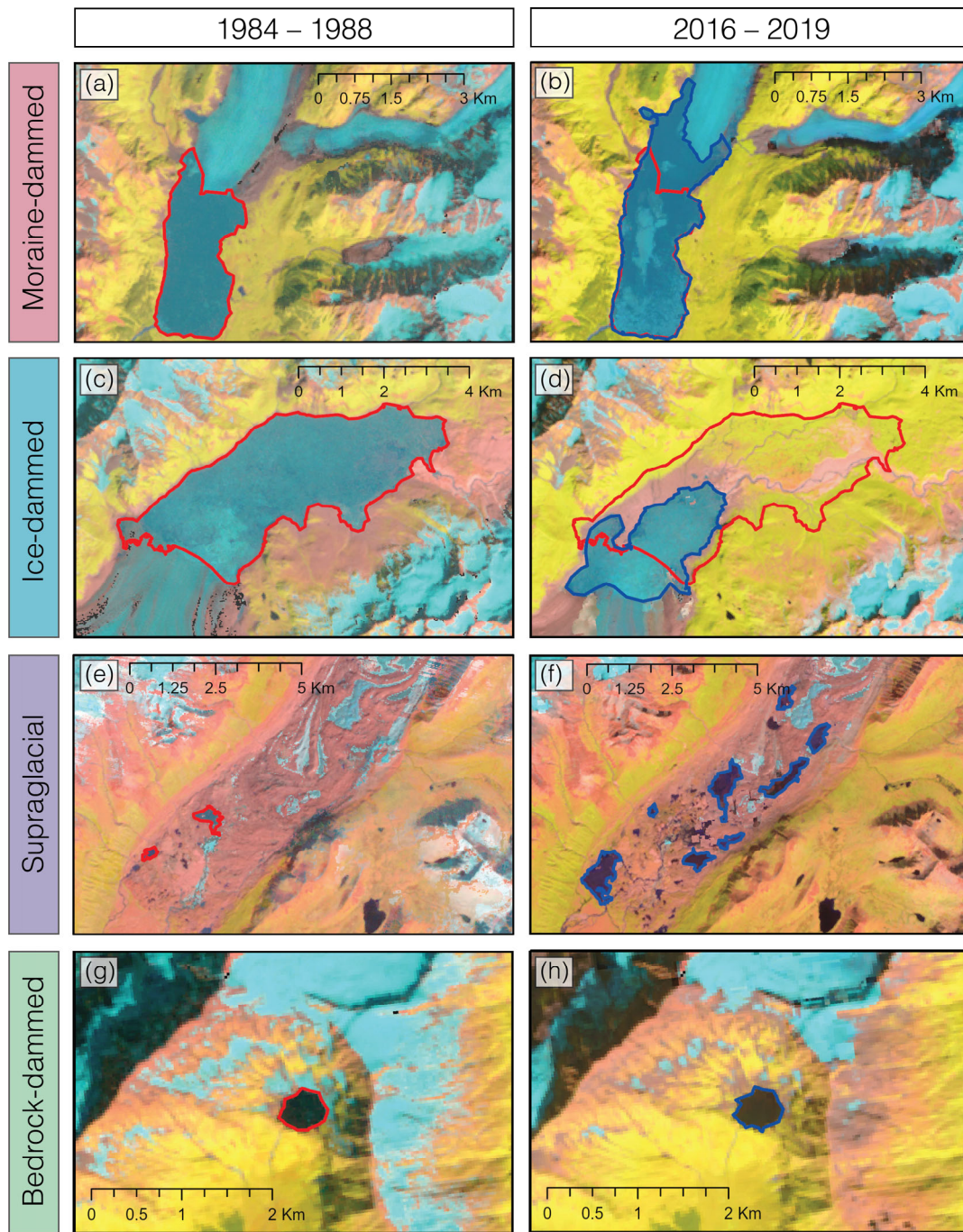
Figure 23: Examples of typical ~~lakes~~lake behavior for each dam type (moraine (a-b), ice (c-d), supraglacial (~~d f~~def), and bedrock(g-h)), and changes in lake area from 1984–1988 (left; red) and 2016–2019 (right; blue). False color images using Landsat bands for shortwave infrared (SWIR), near infrared (NIR), and red.

185

10

2.3.2 Topological position

In addition to dam type, all glacial lakes were classified based on their spatial relationship to their source glacier (Nie et al., 2017; Rounce et al., 2017), into one of the following categories:

i) Proglacial: lakes at the terminus of the glacier, in contact with the ice;

ii) Supraglacial: lakes on the surface of the glacier, most commonly within debris;

iii) Detached: lakes fed by glaciers but not in contact with ice;

iv) Unconnected: detached lakes not fed by glaciers; or

v) Ice: ice-dammed lakes located at ice margins or in tributary valleys.

2.3.3 Lake stability classification

Lake stability simply refers to whether or not a lake is present, rather than the stability of the lake shoreline. Five stability classifications are identified within this dataset:

i) Forms: lakes which appear after 1984–1988 and are present in every mosaic through 2016–2019;

ii) Forms-Drains: lakes which form after 1984–1988 and drain by 2016–2019;

iii) Drains: lakes which were present in 1984–1988 and disappear by 2016–2019;

iv) Drains-Refills: lakes which are present in 1984–1988, are not present for one or two time steps, then reappear by 2016–2019; or

v) Persistent: lakes which are present in all four time steps.

2.4 Lake area change

Absolute area change (ΔA) was calculated for all lakes present in the latest time step (2016–2019), taken as the difference between the last (2016–2019) and first (either 2007–2011, 1997–2001, or 1984–1988) outline for each lake. For lakes which first appear in the 2016–2019 composite, ΔA is equal to lake area in 2016–2019. Rate of change (km^2 per decade, calculated between the midpoint of each interval) was also calculated to minimize bias of longer standing lakes having a larger area change. Rate of change per time step was also calculated to compare rates of area change over time.

2.5 Error

Error in lake delineation was calculated assuming an error of $\pm$ 1 pixel for the entirety of each lake perimeter (Chen et al., 2021):

$$E = P * R, \tag{1}$$

where P is the perimeter of the lake (km), R is the pixel resolution of the imagery (0.030 km for Landsat), and the resulting error (E) is in km^2. This error calculation is more generous than numerous lake inventories which assume $\pm$ 0.5 pixel error (e.g., Fujita et al., 2009; Salerno et al., 2012; Zhang et al., 2015; Nie et al., 2017; Rounce et al., 2017; Wang et al., 2020).

11

Error for the difference in areas was calculated using the theory of propagation of uncorrelated error:

$$E_{diff} = \sqrt{E_x{}^2 + E_y{}^2}. \tag{2}$$

220 ~~where E$_x$~~ Where E_x and ~~E$_y$~~E_y are the error for the first and second lake outlines, respectively. Lakes where the area difference was greater than E$_{diff}$ were determined to have detectable area change.

3 Results

3.1 Lake evolution 1984–1988 to 2016–2019

The overall number of lakes in the Alaska region increased from ~~485~~484 in 1984–1988 to ~~661~~667 in 2016–2019, and total area

225 grew from ~~817.3~~815.5 km^2 in 1984–1988 to ~~1284.4~~1298.5 km^2 in 2016–2019 (Fig. ~~3~~4). The distribution of lakes of each dam type has remained fairly consistent over time, with ~~41~~40–44% of all lakes being moraine-dammed, ~~27~~26–30% bedrock-dammed, 9–14% ice-dammed, and 16–23% supraglacial. However, the contribution of each dam type to the total lake area has changed. The contribution of ice-dammed lakes decreased (16% in 1984–1988 to 6% in 2016–2019), while moraine-dammed lakes increased (67% in 1984–1988 to 79% in 2016–2019). While supraglacial lakes have increased in number over time, their

230 contribution to total lake area has remained consistent around 2–3%. Supraglacial lakes accounted for 20% of lakes by number in 2016–2019, though they only contributed to 3% of the total area. Conversely, moraine-dammed lakes composed ~~39–44~~41% of all lakes yet contributed ~~67~~ to 79% of the total area.
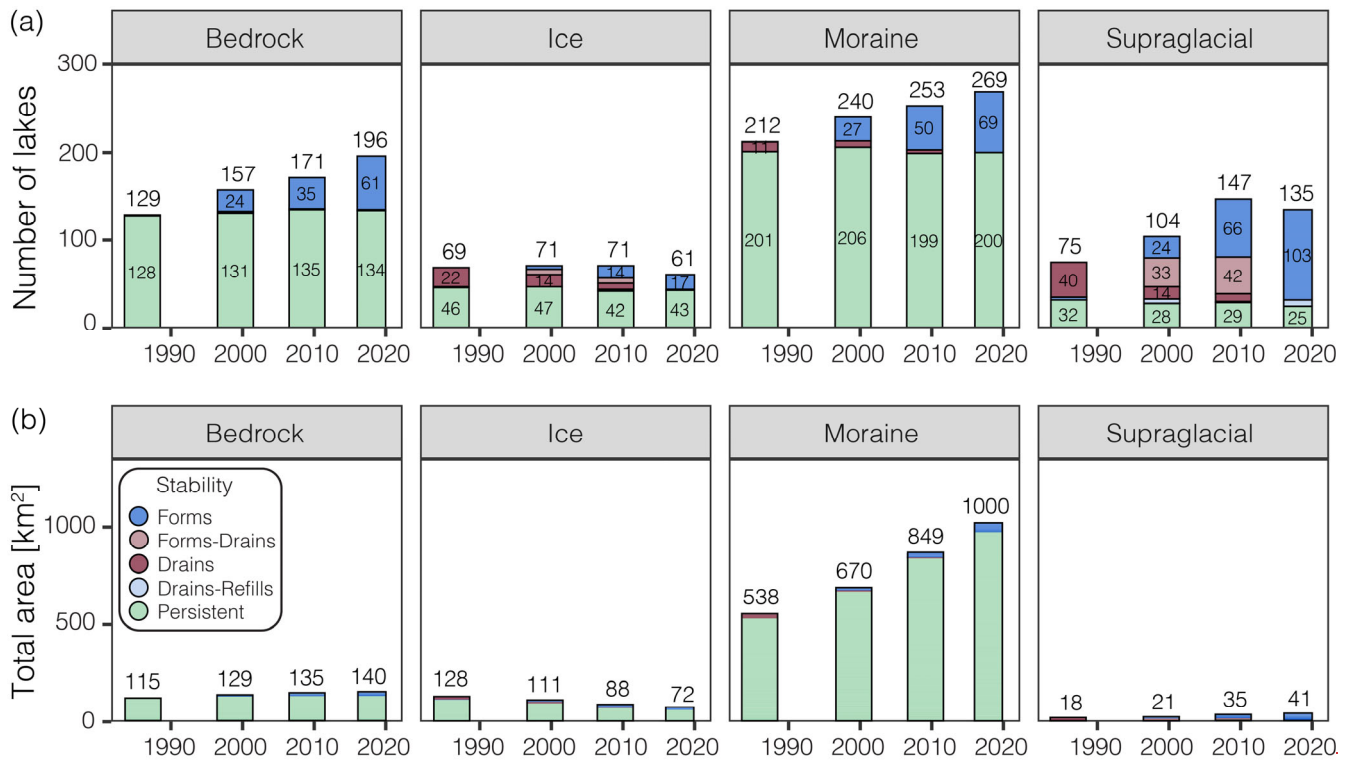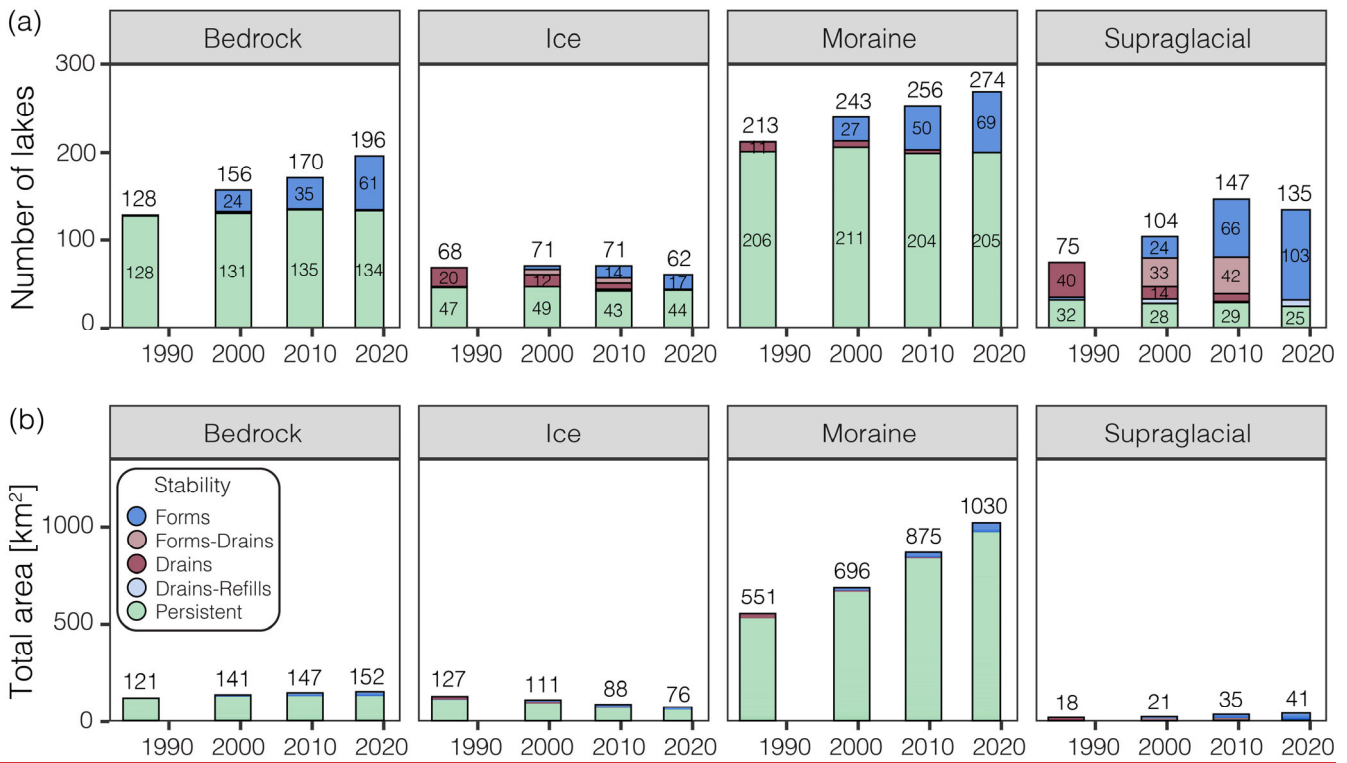
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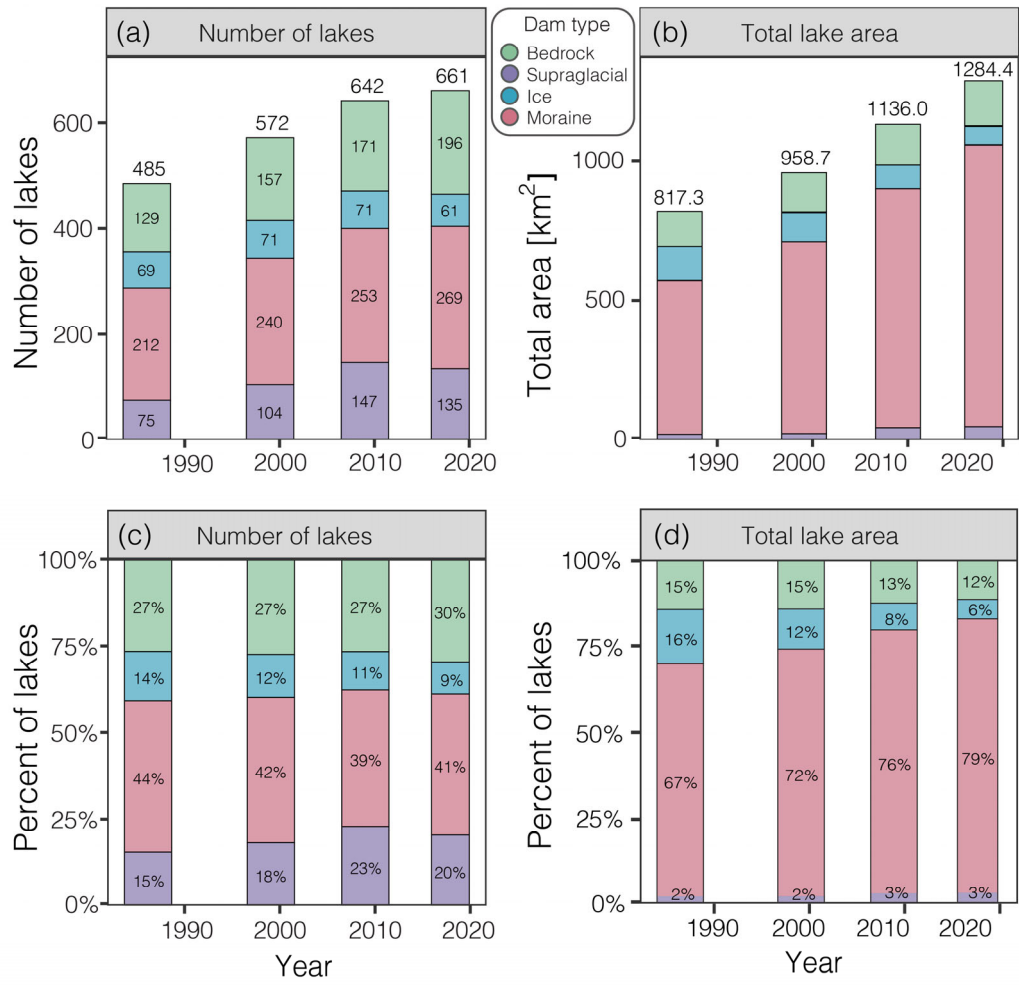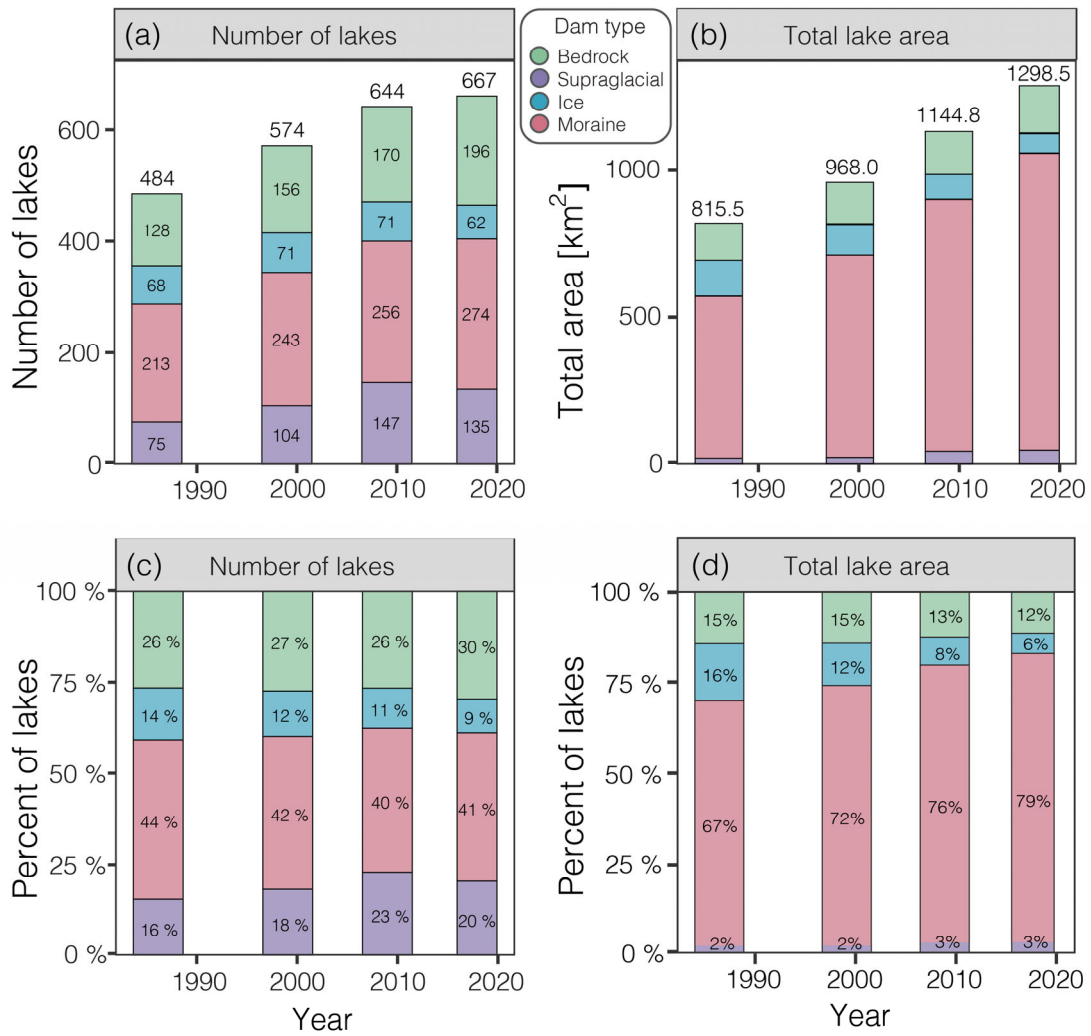
Figure 3̶4: Time evolution of ice-marginal lakes in terms of (a) unscaled number of lakes, (b) unscaled lake area, (c) number of lakes scaled by total number of lakes in that timestep (percent), and (d) lake area scaled by the total lake area in that timestep (percent). Lakes are colored by lake dam type (legend between panels a and b). Bar widths correspond to imagery time intervals.

Lake stability describes whether a lake is persistent, or if it formed or drained during any of the four time intervals used for analysis. Lakes that appear in all four time intervals ("persistent lakes") dominate both the number and area of bedrock-, ice-, and moraine-dammed lakes (Fig. 4̶5). Supraglacial lakes are the least stable, as this class is dominated by non-persistent lakes. Changes in the number of persistent lakes from ~~year~~interval to ~~year~~interval is due to lakes either splitting or merging. The rate of formation of new bedrock and moraine-dammed lakes appears relatively constant over time, with ~10–30 new lakes of each dam type first appearing in each time interval.

(a)

Bedrock | Ice | Moraine | Supraglacial

Year	Bedrock	Ice	Moraine	Supraglacial
1990	129 (128)	69 (22, 46)	212 (201)	75 (40, 32)
2000	157 (24, 131)	71 (14, 47)	240 (27, 206)	104 (24, 33, 28)
2010	171 (35, 135)	71 (14, 42)	253 (50, 199)	147 (66, 42, 14, 29)
2020	196 (61, 134)	61 (17, 43)	269 (69, 200)	135 (103, 25)

(b)

Bedrock | Ice | Moraine | Supraglacial

Stability
- Forms
- Forms-Drains
- Drains
- Drains-Refills
- Persistent

Year	Bedrock	Ice	Moraine	Supraglacial
1990	115	128	538	18
2000	129	111	670	21
2010	135	88	849	35
2020	140	72	1000	41

15

Figure 45: **Number of lakes (a) and total area (b) of each dam type through time.** <u>The number of lakes in blue indicates the total number of lakes in that time period that were not present in 1984–1988; the number of lakes in red indicates the number of lakes present in that time period which drain in a subsequent time period. Light red indicates lakes which form after 1984–1988 but drain before 2016–2019.</u> **Bar widths correspond to imagery time intervals.**

Moraine-dammed lakes added ~~58~~56 lakes (+~~27.5~~26%) and grew by ~~468.5~~479 km² (+~~85~~87%) from 1984–1988 to 2016–2019, while bedrock-dammed lakes added 68 lakes (+~~52.7~~53%) and grew by 31.8 km² (+26.~~3~~%; Fig. 45). Though they added a similar number of lakes, moraine-dammed lakes increased in total area more rapidly than bedrock-dammed lakes, primarily through the growth of pre-existing lakes.

While bedrock and moraine-dammed lakes steadily increased in lake frequency and area, supraglacial lakes exhibited more variability. This class increased by 72 lakes from 1984–1988 to 2007–2011, yet lost ~~13~~12 lakes from 2007–2011 to 2016–2019, resulting in an overall increase of ~~59~~60 lakes (~~78~~80% increase). Despite varying frequency, supraglacial lakes grew in total area between each time period, resulting in a total increase of 22.8 km² (+127%) from 1984–1988 to 2016–2019. Supraglacial lakes had the largest percent increase in area; however, they contributed the least (2–3%) to total lake area across different dam types.

16

Ice-dammed lakes are the only dam type with decreasing number and area, losing ~~9~~6 lakes (~~-13~~9%) and ~~56~~51 km² (~~-43~~40%) overall from 1984–1988 to 2016–2019. However, a total of ~~22~~20 individual lakes drained and ~~16~~17 formed throughout this time period, with an additional three lakes merging, resulting in an overall loss of six lakes.

Lake frequency and area change distribution varies with lake area (Fig. ~~5~~6). A majority of lakes (~~84~~77%) are less than 1 km², yet they ~~compose~~ contribute to just ~~13~~6% of the total area change from 1984–1988 to 2016–2019. Moraine-dammed lakes dominate the proportion of lakes greater than 1 km². There are ~~11~~19 lakes (~~10~~17 moraine-dammed, ~~1~~one bedrock-dammed, and one ice-dammed) with individual areas greater than ~~20~~10 km², accounting for ~~250.8~~288.7 km² (~~54~~60%) of the total area growth from 1984–1988 to 2016–2019. ~~Moraine-dammed lakes dominate the proportion of~~Excluding lakes greater than ~~1~~10 km²~~.~~, the total lake area in the Alaska region grew by 41.5% (compared to the 59% area increase when considering all lakes).


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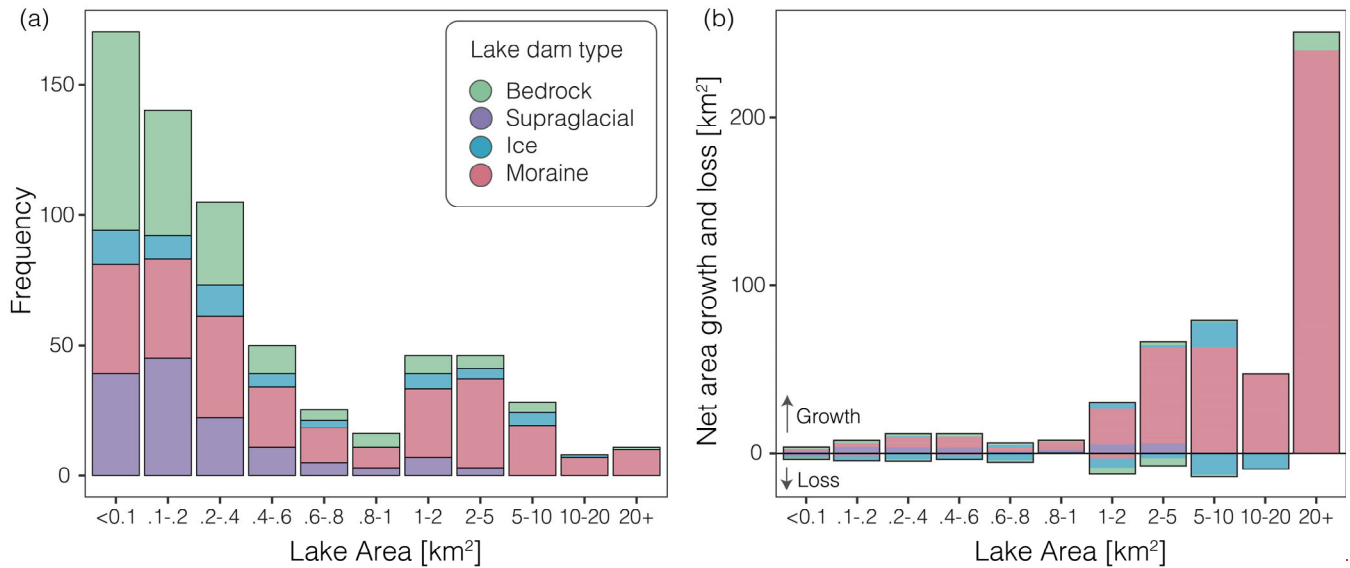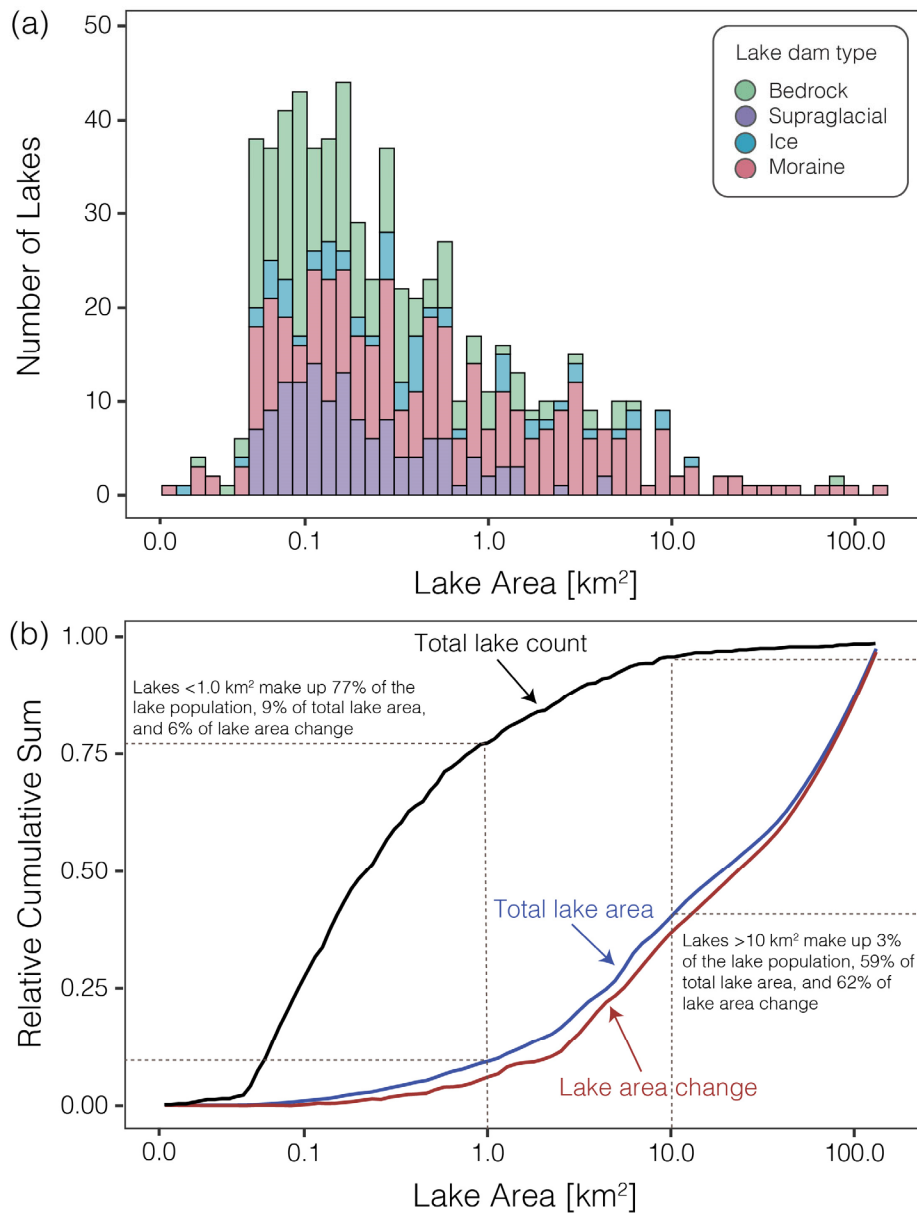
Figure ~~5~~6: Distribution of lake area frequency in 2016–2019 ~~(~~by lake area (colored by dam type; **a) and** relative cumulative sum of total lake number, total lake area, and total **lake area change** ~~from~~ (1984–1988 to 2016–2019 ~~(; b) for different sized lakes. (b) sums area loss and gain within in each dam type, showing the range of behavior within a single size class rather than total area change which masks area loss.).~~ **Note** ~~: bins include varying ranges of lake area~~ that the x-axis is logarithmic.

3.2 Individual lake area evolution

From 1984–1988 to 2016–2019, 791 distinct lakes were identified, ~~661~~667 of which were still present in 2016–2019. Of the 124 lakes which drained, 97 (78%) were supraglacial, 20 (16%) were ice-dammed, and 7 (6%) were moraine-dammed. Absolute area change was calculated for each individual lake, with drained lakes considered to have an area of zero km^2 after

18

285 drainage (Fig. ~~6~~7). Detectable change (error < area change) occurred for 334 of the total 791 lakes (44%). Within each dam type, 63% of moraine-dammed, 45% of ice-dammed, 39% of supraglacial, and 24% of bedrock-dammed lakes experienced detectable change.
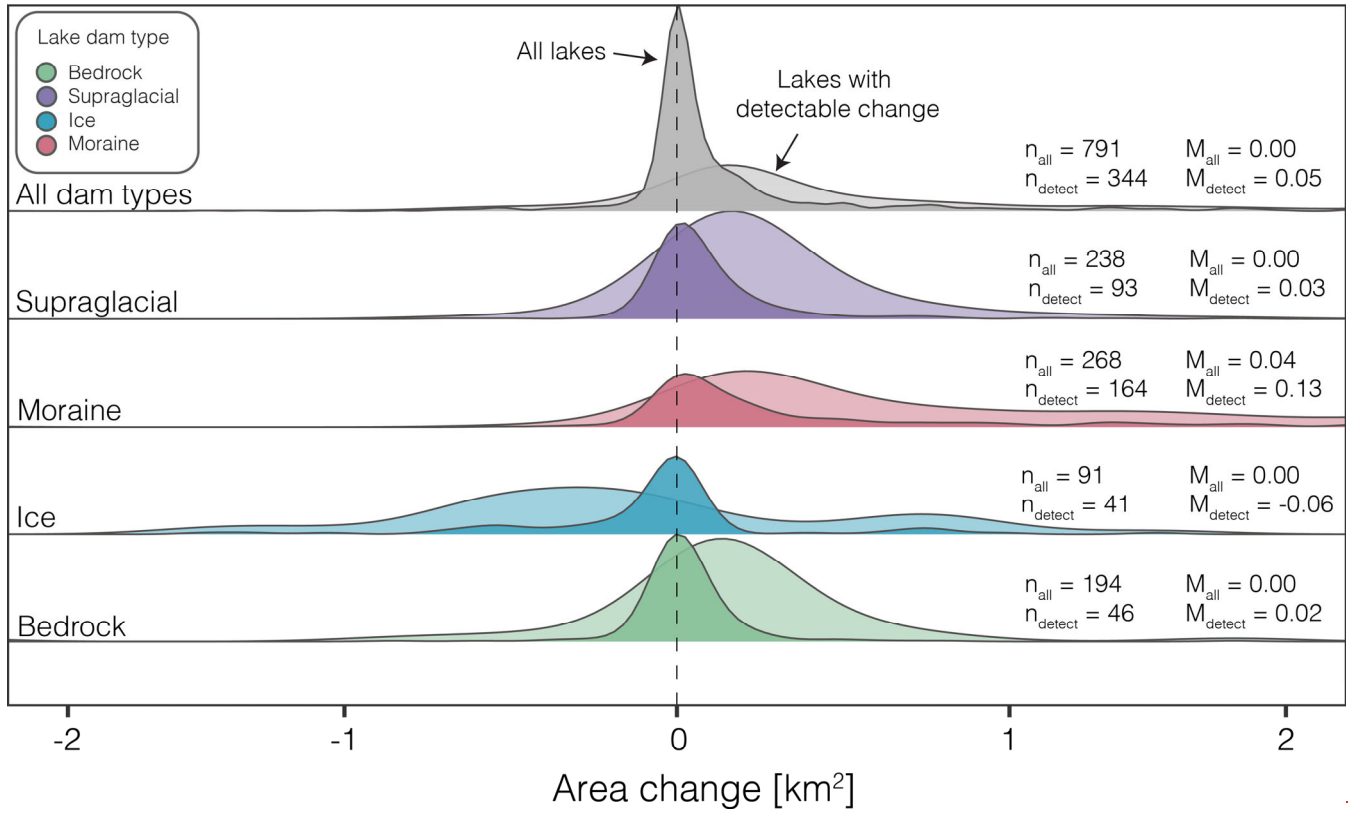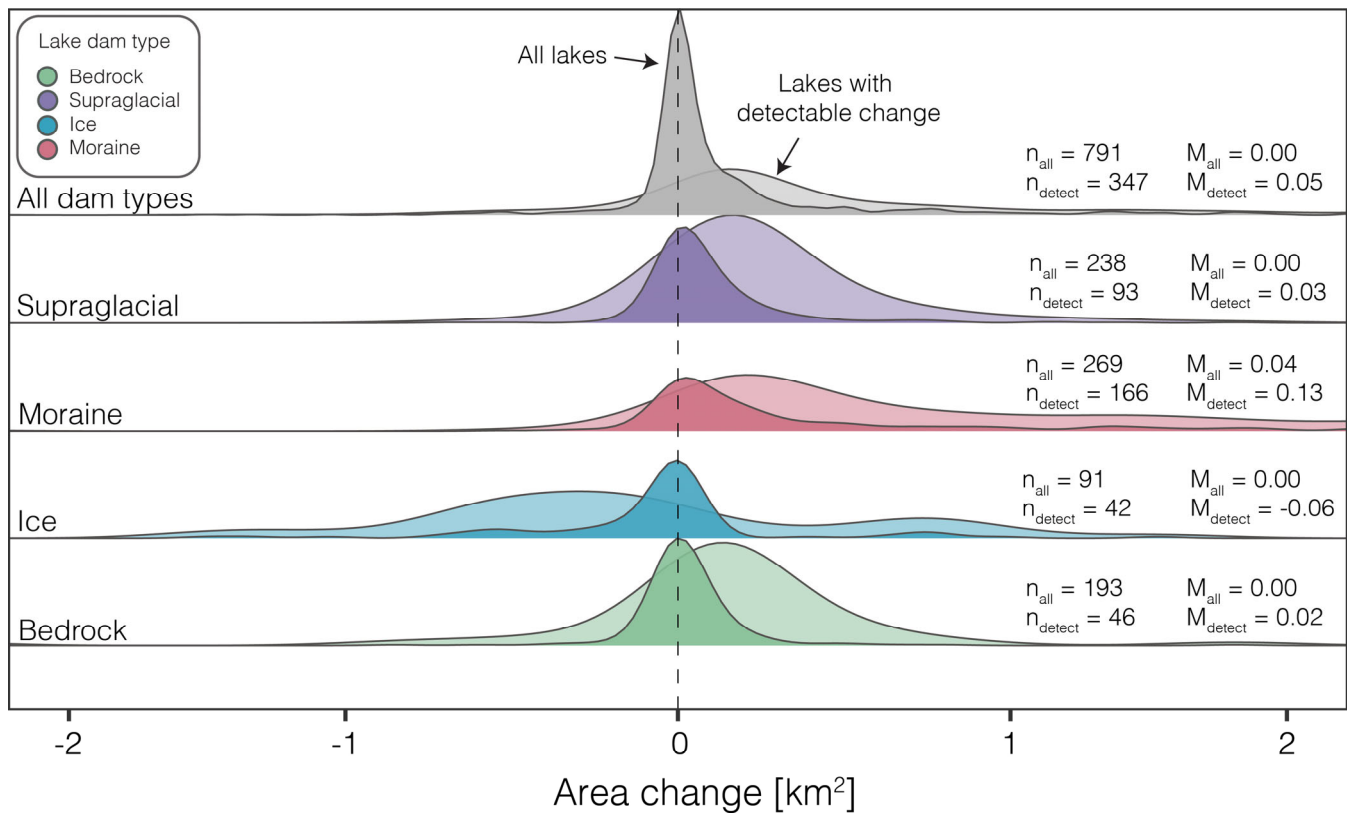
Figure 6̶7: Smoothed density distribution (normalized to 1 for each dam type) of absolute lake area change for all lakes (dark curves) compared to that for only lakes with detectable change (light curves) for each dam type, with number of lakes (n) and median lake area change (M). Note that the x-axis has been limited to -̶-2 and 2 km². For the full distribution, see Fig. S̶4̶S5.

~~The median area change for lakes of all dam types (n = 791) is 0.00 km², while the~~The median area change for lakes of all dam types with detectable change (n = 344) is 0.05 km² between 1984–1988 and 2016–2019. ~~When considering all lakes within each dam type, ice-dammed (n = 91), supraglacial (n = 239), and bedrock dammed (n = 194) lakes all have a median area change of 0.00 km², while moraine dammed lakes (n = 267) have a median area change of 0.04 km²~~. (Fig. 7). Considering only lakes with detectable change, the median change for moraine-dammed lakes (n = 1̶6̶3̶166) is 0.13 km², ice-dammed lakes (n = 42) is –0.06 km², supraglacial lakes (n = 93) is 0.1̶4̶03 km², ~~ice-dammed~~and bedrock-dammed lakes (n = 46) is 0.02 km². Median change values remain relatively stable even when lakes ~~(n = 41) is~~> 10 km² are excluded from analysis (Fig. S6). ~~–0.06 km², supraglacial lakes (n = 94) is 0.04 km², and bedrock dammed lakes (n = 46) is 0.02 km².~~

Proglacial lakes (moraine- and bedrock-dammed) experienced the largest median detectable change (0.~~06 km² all, 0.~~14 km² ~~detectable~~), while ice-dammed lakes are the only dam type to experience negative median detectable change (–0.06 km² ~~detectable~~; Table 2; Fig. S̶5̶S7). Unconnected and detached lakes have ~~a median change of 0.00 km² when considering all lakes, and~~ a median change of 0.02 km² for lakes with a detectable change. Proglacial moraine-dammed lakes have a wider

20

distribution and higher median change than detached or unconnected moraine-dammed lakes (Table 2). Proglacial moraine-dammed lakes also have a wider distribution and higher median change than proglacial bedrock-dammed lakes.

Table 2: Count (area, km^2) of glacial lakes by dam type and location between 1984 and 2019, as well as median area (km^2)), range of areas (km^2), and median area change (km^2) for all lakes. Median area change for lakes with detectable change (km^2) are within the parentheses.

Dam Type	Location	1984–1988	1997–2001	2007–2011	2016–2019	Change 1984–88 to 2016–19	Median area	Area range	Median Med change 1984–88 to 2016–19
Moraine	Proglacial	171172 (539)	190 (664193 (674)	190 (839193 (849)	197 (988201 (999)	26 (449460)	0.71	0.01–143.1	0.3 (0.7775)
	Detached	3637 (9.56)	4546 (19.23)	5859 (24.45)	6869 (28.78)	32 (19.2)	0.12	0.02–5.9	0.0 (0.08)
	Unconnected	4 (2.1)	4 (2.2)	4 (2.0)	4 (2.0)	0 (-0.1)	0.40	0.05–1.2	0.0 (0.0)
Bedrock	Proglacial	12 (4.0)	10 (2.7)	13 (5.0)	1716 (7.51)	54 (3.51)	0.19	0.04–2.2	0.1 (0.19)
	Detached	5857 (92.76)	7675 (103)	7877 (105)	85 (106)	2728 (13.34)	0.13	0.03–76.4	0.0 (0.11)
	Unconnected	59 (23.9)	71 (35)	80 (36.7)	95 (38.7)	36 (14.8)	0.16	0.02–5.6	0.0 (0.09)
Ice	Tributary	43 (11542 (113)	41 (96.0)	44 (71.43)	36 (62.738 (66.2)	7 (52.3 −4 (−46.8)	0.75	0.01–22.0 (0.37)	0.0 (−0.36)
	Margin	26 (13.4)	30 (14.9)	27 (16.9)	24 (9.576)	−2 (−3.838)	0.16	0.03–7.0	0.0 (−0.13)
Supraglacial		7675 (17.98)	105104 (21.41)	148 (35.1147 (34.7)	135 (40.7)	5960 (22.89)	0.12	0.0 (0.04)03–4.1	0.0 (0.03)
Total		485 (817.3484 (815.5)	572 (958.7574 (968.0)	642 (1136.0644 (1145)	661 (1284.4667 (1298.5)	176 (467.1183 (483.0)	**0.21**	0.01–143.1	0.0100 (0.21)

Rate of area change (km^2 per decade) follows a similar distribution as absolute area change (Fig. S6). When assessing all dam types together (n = 791), the median change rate is 0.00 km^2 per decade.S8). The median change rate for lakes of all dam types with detectable change (n = 344) is 0.02 km^2 per decade. When considering all lakes within each dam type, moraine-dammed lakes are the only dam type with a change rate greater than zero (0.05 km^2 per decade). Supraglacial and bedrock-dammed lakes experience very small changes on a decadal scale, with a median change rate of 0 for all lakes as well as the subset of detectable lakes. Ice-dammed lakes with detectable change experienced a median change rate of –0.02 km^2 per decade.

21

3.3 Regional lake distribution

Distribution of lake dam type and total lake area varies spatially by subregion (Table 3; Fig. ~~7~~8), though median lake area change does not vary substantially when considering all lakes with detectable change per region (ranges from 0.04–0.06 km^2). Ice-dammed lakes occur most frequently in the St. Elias Mountains (n = 26 in 2016–2019) and least frequently in the W. Chugach Mountains (n = 6 in 2016–2019), Brooks Range (n = 0), and the Aleutians (n = 0). The N. Coast Ranges are dominated by moraine- and bedrock-dammed lakes, whereas the Alaska Ranges and St. Elias Mountains are dominated in number by supraglacial lakes. Supraglacial lakes occur in the regions with the highest debris cover (19% of glacier area in the Alaska Ranges, and 13% in the St. Elias Mountains; Herreid and Pellicciotti, 2020). However, supraglacial lakes contribute little to the total lake area. The number of lakes within a region does not directly predict area; the N. Coast Ranges host the highest number of lakes (n = 234, 382.5 km^2), yet the St. Elias Mountains have the greatest total lake area (n = 181, 545.5 km^2).

Table 3: Number of lakes, glacierized area, debris covered area, percent debris cover, normalized lake frequency, normalized lake area, normalized lake area change, and specific glacier mass balance (from Jakob et al., 2021) per subregion.

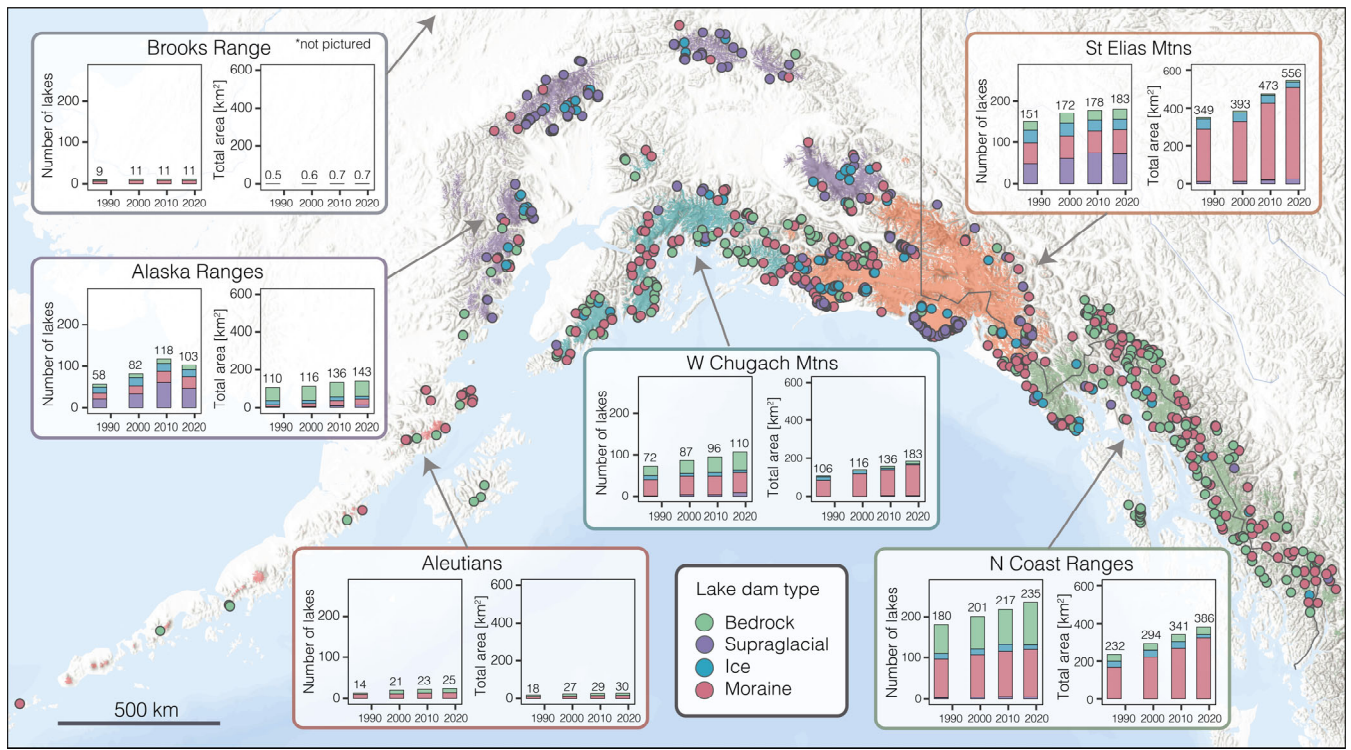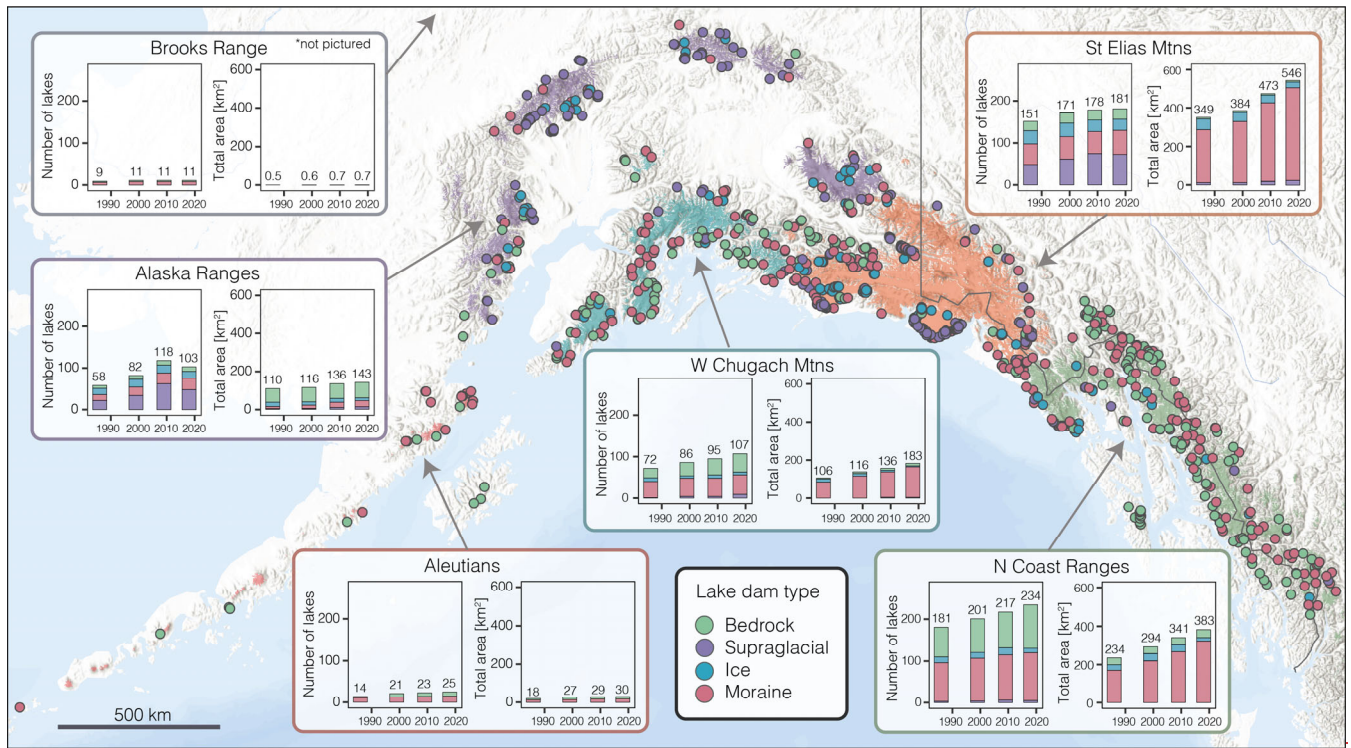| Region	# of lakes 2016–19	Total glacier area (km^2)	Total debris cover (km^2)	Total lake area (km^2)	Percent debris cover	Normalized lake freq (# per 100 km^2 ice)	Normalized lake area (km^2 per 100 km^2 ice)	Normalized lake area change (km^2 per 100 km^2 ice)	Specific mass balance (m w.e. yr^{-1})
Brooks Range	11	346	10.3	0.7	3.0	3.2	0.2	0.1	N/A
Alaska Ranges	103	16278	3135.5	143.0	19.3	~~.6~~30.6	0.9	0.2	~~- -~~0.41 ± 0.05
Aleutians	25	1912	198.7	30.0	10.4	1.3	1.6	0.6	~~-~~0.64 ± 0.10
Chugach Mtns	107	12052	586.2	182.8	4.9	0.9	1.5	0.6	~~-~~0.80 ± 0.09
St. Elias Mtns	181	33174	4446.3	545.5	13.4	0.5	1.6	0.6	~~-~~1.03 ± 0.10
N Coast Ranges	234	22963	1553.8	382.5	6.8	1.0	1.7	0.6	~~-~~1.08 ± 0.09

23

Figure ~~7~~8: Dam type distribution (spatial, frequency, and total area) for each Alaska subregion. Note: Brooks Range not pictured on map~~.~~: see Fig. 1. Basemap provided by ESRI, 2021.

340

Persistent lakes dominate the total area for each subregion, likely because new lakes tend to be small. The N~~.~~ Coast Ranges have the most persistent lakes (n = 175 in 2016–2019), with 57 lakes forming yet contributing little to the total area (Fig. ~~S7~~S9). Changes in persistent lake numbers between time steps is due to lakes splitting or coalescing through time. The Alaska Ranges and St. Elias Mountains have the largest number of lakes that ultimately drain, likely due to the high frequency of

345   supraglacial lakes in these regions and their spatial and temporal heterogeneity.

4 Discussion

Our inventory of ice-marginal lakes in Alaska from 1984 to 2019 demonstrates that lake area changes vary based on lake dam type and a lake's topological position. By tracking individual lakes through time and categorizing lakes by dam type, region, and spatial relationship to their source glacier, we are able to ~~parse~~identify trends that would otherwise be overlooked if lakes

350   within Alaska were considered as a whole.

Overall, ice-marginal lakes in Alaska have grown in both number and area between 1984 and 2019, following the trend in both regional (Wang et al., 2013; Carrivick and Quincey, 2014; Nie et al., 2017; Song et al., 2017; Emmer et al., 2020) and global (Shugar et al., 2020) studies. However, ice-dammed lakes have decreased in number and area whereas moraine-dammed lakes have increased at a faster rate than the average when considering all dam types together. By examining individual lakes, we

355   identify that the majority (56%) of lakes have not experienced a detectable area change over the period of study, and that ~~11~~19 large~~,~~ (>10km^2), primarily moraine-dammed lakes contributed to ~~54~~60% of total area growth. Analyzing all dam types together would fail to identify decreases in number and area of ice-dammed lakes, underestimate the increases in proglacial moraine-dammed lakes, and likely overestimate the importance of the appearance of small, supraglacial lakes.

4.1 Alaska's ice-marginal lakes

360   Lake ~~location~~position and dam type, which are often linked, provide a simple, physically-based metric for parsing ice-marginal lakes in Alaska. The majority of moraine-dammed lakes are proglacial, located behind a Little Ice Age (LIA; ~1250–1850 AD) moraine at the front of a retreating glacier (e.g., Wiles et al., 1999; Santos and Córdova, 2009; Solomina et al., 2015, 2016). They tend to be associated with clean-ice glaciers (82%), defined by Brun et al. (2019) as <19% debris cover (Fig. ~~8~~9). The growth rate of moraine dammed lakes appears to be coupled to the amount of debris cover, as the lakes with the largest

365   area increase are associated with clean-ice glaciers, with the exception of Vitus Lake at Bering Glacier (Fig. 9). Moraine-dammed lakes occur with both large and small glaciers, as most temperate glaciers can form a moraine during a period of advancement (e.g., the LIA), as long as sediment supply to the terminus is high. Basin geometry and glacier hypsometry likely play a large role in determining the lake expansion rate and maximum lake area, as the underlying bed slope influences how

24

quickly the glacier retreats (depending on glacier mass balance; see Sect. 4.5). For example, large, coastal proglacial lakes can

370 fill piedmont lobe basins (such as Vitus Lake, Malaspina Lake, and Grand Plateau Glacier Lake), which accommodate larger
lake expansion than proglacial lakes confined to smaller, steeper valleys (Field et al., 2021). Basin geometry also determines
the maximum lake level and the point at which the glacier detaches from the lake.
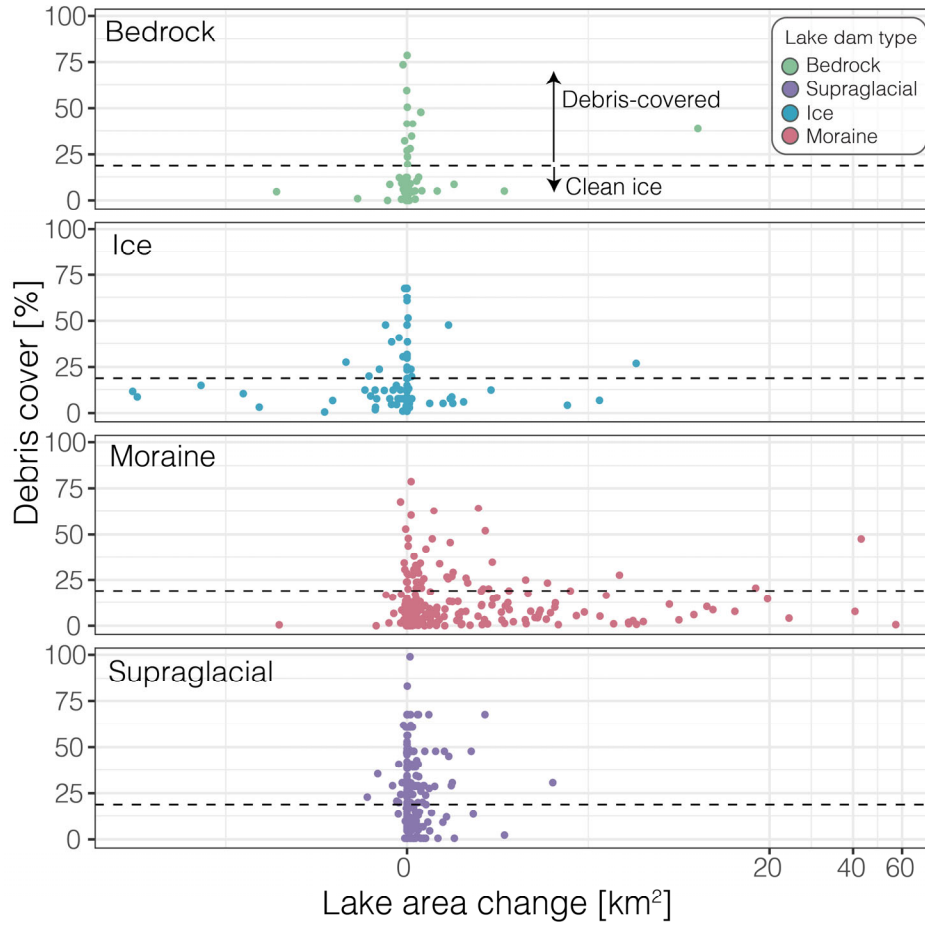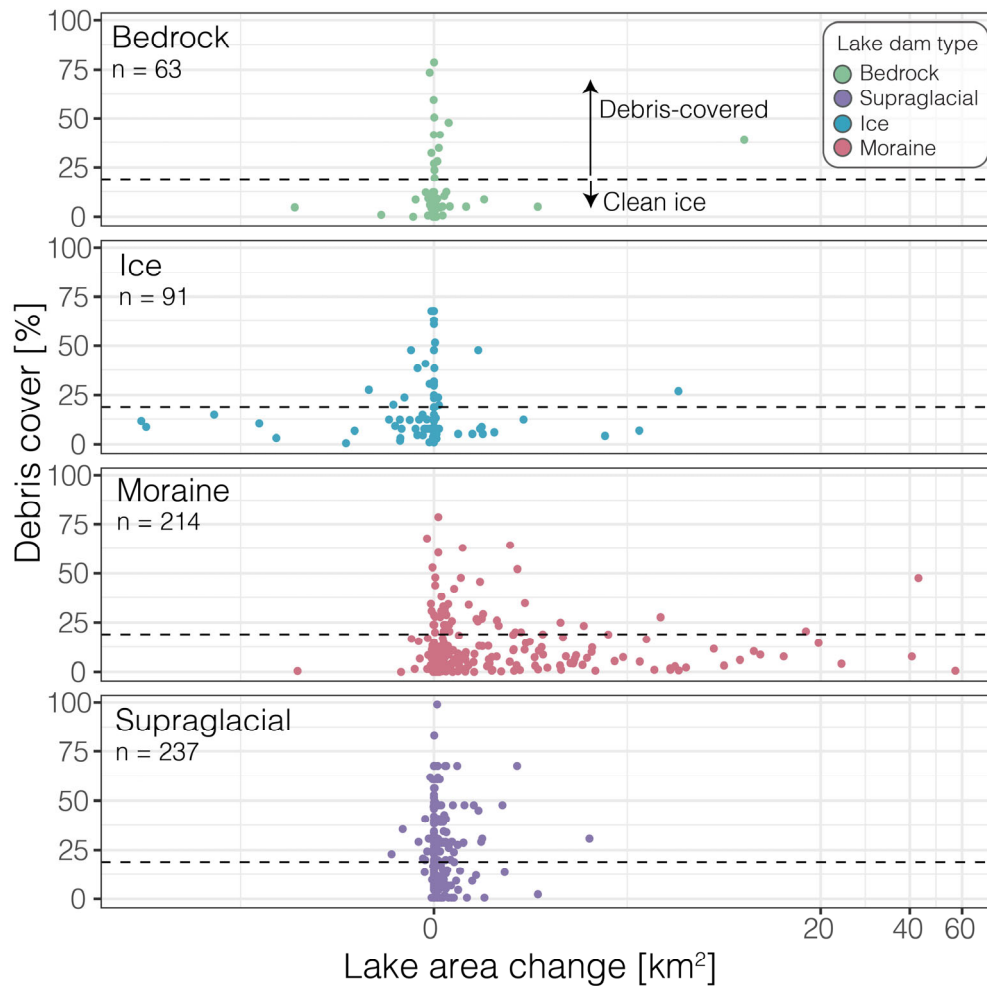
Figure 8.9: Percent glacier debris cover vs lake area change (km²) for lakes associated with glaciers > 2 km². Each dot represents an individual lake. Dashed line is at 19%, above which is considered debris-covered ice and below is considered clean ice (Brun et al., 2019).

Ice-dammed lakes are primarily located next to clean-ice glaciers (65%), with larger, lower slope areas and positive hypsometric indices (bottom-heavy; Fig. ~~9).~~10), such as are found adjacent to Brady Glacier (Capps et al., 2011; Pelto et al., 2013). The largest lakes occur in tributary valleys, dammed by main branch ice, while many small lakes are found in pockets between glacier margins and valley walls. The decrease in ice-dammed lake number and area is likely due to the down-wasting of glacier surfaces (e.g., Larsen et al., 2015; Jakob et al., 2021), decreasing the height of the ice dam and therefore decreasing maximum area (and volume) of the lake (e.g., Kienholz et al., 2020). The formation of new conduits alongside or beneath the glacier could also be influencing ice-dammed lake drainage ~~(Post and Mayo, 1971). Though not explicitly examined in our study, ice thinning was~~(e.g., Tulsequah Glacier; Neal, 2007; Post and Mayo, 1971). Previous work documented ice thinning

26

the primary factor in the loss of an ice dam for 82% of lakes lost from land-terminating glaciers and 62% of loss from lake terminating glaciers between 1971 and 2008 (Wolfe et al., 2014).

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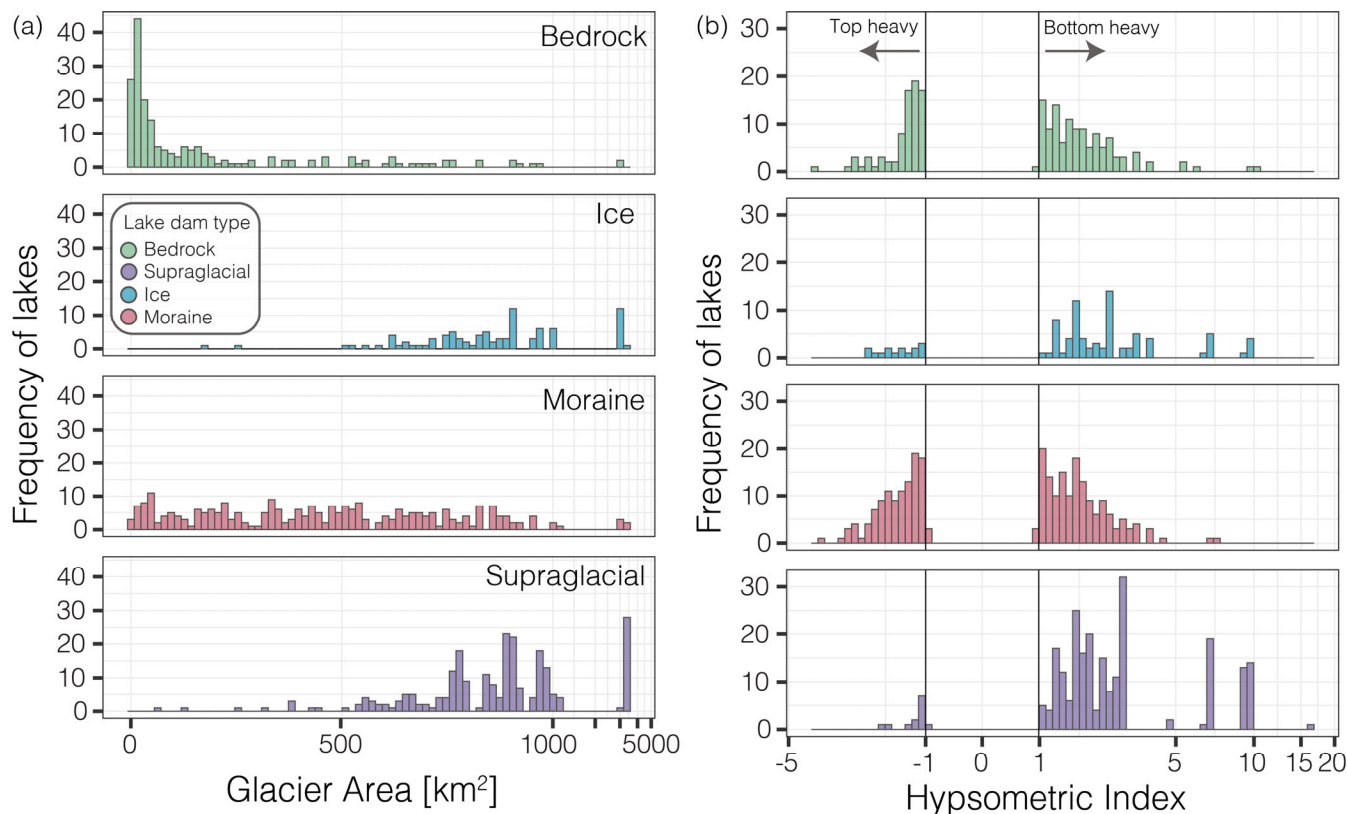
Figure 9.10: Histogram of number of lakes and associated glacier area, separated by dam type (a) and histogram showing number of lakes within each hypsometric index (HI) bin, separated by dam type (b). Hypsometric index was calculated by McGrath et al. (2017). HI values greater than 1 indicate a bottom heavy glacier, HI values less than –1 indicate a top heavy glacier. Note the logarithmic x-axis scales.

395

An overwhelming majority (>80%) of bedrock-dammed lakes are associated with clean-ice glaciers less than 10 km^2 in area (Figs. 8 & 9 and 10). These types of lakes generally form within cirques, where a small glacier has retreated and exposed an overdeepening. Bedrock-dammed lakes can indicate an advanced stage of lake development (Emmer et al., 2020), such as is found in parts of the N. Coast Ranges. Most bedrock-dammed lakes (>90%) are either detached or unconnected, with minimal influence from ice-water contact. The small changes in area of unconnected bedrock-dammed lakes could be due to changes in the regional water balance rather than glacier dynamics.

Supraglacial lakes generally form on low-sloped debris-covered tongues of glaciers (Reynolds, 2000), where thin debris enhances melt and thick debris insulates ice and reduces surface melt (Östrem, 1959), often leading to heterogeneous surficial topography. Debris cover tends to reduce ice discharge and surface melt, leading to longer glaciers (Anderson and Anderson,

27

2016). The inventoried supraglacial lakes in Alaska follow these trends, with their distribution strongly skewed towards flat, bottom-heavy glaciers, as is characteristic of debris-covered glaciers (Reynolds, 2000). These lakes can occur on glaciers with any amount of debris cover, though have the highest concentration (64%) out of any lake dam type on glaciers with >19% debris cover (Fig. 89). A majority of supraglacial lakes are located on a few large, heavily debris covered glaciers. For example, 95% of supraglacial lakes in the St. Elias Mountain region are located on two large, piedmont glaciers (Malaspina and Bering glaciers). Although these lakes are abundant, they exhibit high spatiotemporal variability and contribute minimally to total lake area (2–3%; Fig. 45).

Although additional factors– are required to comprehensively– assess GLOF hazards,– a lake inventory that captures area and dam type–and provides a foundation for this type of assessment, as dam type influences stability, lake volume are primary indicators of likelihood of a dam to fail and the potential magnitude of a flood. Lake volume scales with area– (e.g.,– Huggel et al., 2002; Cook and Quincey, 2015), and peak flood discharge scales with volume (e.g., Walder and Costa, 1996; Veh et al., 2020). and peak flood discharge scales with volume (e.g., Walder and Costa, 1996; Veh et al., 2020). Ice-dammed lakes are known to undergo multiple fill/drain cycles with the capability of producing multiple GLOFs (e.g., Anderson et al., 2003; Jacquet et al., 2017), whereas moraine-dammed lakes tend to only GLOF once, as their dam is typically compromised in the process. The observed decrease in number and area of ice-dammed lakes in Alaska suggests an overall decrease in GLOF hazards from these types of lakes, although the specifics of remaining lakes need to be evaluated on a case by case basisindividually (e.g., Suicide Basin, Kienholz et al., 2020).Kienholz et al., 2020; Tulsequh Glacier, Neal, 2007; Bear Glacier, Wilcox et al., 2014). The increase in number and area of moraine-dammed lakes provides a greater number of potential source lakes and a larger potential flood volume, however, factors such as surrounding slope stability (e.g., landslides, rockfalls, permafrost), moraine geometry and stability (e.g., slope, presence of an ice core), and downstream impacts must be evaluated first to determine GLOF potential and hazard (e.g., Worni et al., 2013; Rounce et al., 2017). As the nature of the dam type influences lake stability, the opposing trends of ice-dammed and moraine-dammed lakes complicates a region-wide assessment of changing GLOF hazards in the Alaska region.

4.2 Regional trends

The Alaska region of the RGI is separated into six second-order regions (see Fig. 8), used here as subregions for analysis. Lakes are most numerous in the N. Coast Ranges (35% of all lakes) and St. Elias Mountains (27%), though these ranges also have the largest glacier area (24% and 41% of total ice in Alaska, respectively). Normalized lake frequency (number of lakes per 100 km^2 of glaciers) is highest in the Brooks Range, though it has the lowest normalized lake area (lake area per 100 km^2 of glaciers; 0.2) as total lake area sums to just 0.7 km^2 (Table 3). We interpret these normalized lake statistics as reflecting the late stage of ice-marginal lake development, minimal LIA glacier advance, as well as the relatively small glacier extent in the Brooks Range even during the last glacial maximumLast Glacial Maximum (Kaufman and Manley, 2004). Normalized lake area is highest in the N. Coast Ranges (1.7 km^2 per 100 km^2 of glaciers) due to the abundance of smaller glaciers and many

28

proglacial lakes. The St. Elias Mountains have the largest total lake area; however, it also contains large icefields, which results in a similar normalized lake area as the Aleutians and the Chugach Mountains (1.5–1.6 km^2 per 100 km^2 of glaciers). This suggests that the area of ice-marginal lakes scales with glacier area in the coastal ranges (i.e., excluding the Brooks Range and Alaska Ranges), with normalized lake area ranging from 1.5 to 1.7.

Accounting for lake area change, the Brooks Range and Alaska Ranges have a small normalized lake area change (0.1–0.2; lake area change between 1984 and 2019 per 100 km^2 of glaciers). The Chugach, Aleutians, St. Elias, and N. Coast Ranges, however, each have a higher normalized lake area change (0.6). These numbers suggest a dichotomy in which coastal glacier-lake systems are changing faster than those in more interior settings, in agreement with recent work investigating physical controls on ice-marginal lake area change (Field et al., 2021). The Alaska Ranges have the highest percent debris cover (19%), which could be a factor in the low normalized lake area and normalized lake area change seen in this region. Supraglacial lakes are the most abundant dam type in the Alaska Ranges (47% in 2016–2019), characterized by small areas and area changes (Table 2).

4.3 Temporal trends

Rate of lake area change (km^2 per decade) through time indicates whether ice-marginal lake evolution has remained constant between different time periods, or whether the lakes have experienced periods of accelerated or decelerated change. Bedrock dammed lakes experienced little variation in rate of area change throughout the period of study (Fig. ~~10~~11), with a rate that hovers around zero, likely due to the fact that a majority (>90%) of bedrock-dammed lakes are either detached from their associated glacier or unconnected to any glacier. Ice-dammed lakes consistently experienced a negative median rate of area change, with the most negative rate of growth between 2007–2011 and 2016–2019. This implies drainage of ice-dammed lakes may be accelerating, which could be due to an increased rate of glacier thinning since 2013–2014 (Jakob et al., 2021), though this link requires further investigation. Supraglacial lakes exhibit the opposite trend, growing at a faster rate after 2007–2011 than they did prior. Moraine-dammed lakes experienced the largest median rate of change between 1984–1988 and 1997–2001. A decreasing median rate of change for moraine-dammed lakes yet large total area growth is likely due to the growth of a few large, outlier lakes whose influence is minimized by comparing median rather than mean rates of change. Proglacial lakes experienced the overall largest rate of growth, even when compared to all moraine-dammed lakes, suggesting that topological position, rather than strictly dam type, is a better indicator for rate of ice-marginal lake area change. Together, these data suggest the ice-marginal lakes of Alaska and northwestern Canada could be undergoing a transition, with ~~the dominant mechanism for~~an increased role of supraglacial lakes driving regional lake area ~~change shifting from moraine-dammed lake~~ expansion ~~to growth and coalescence of supraglacial lakes in the future~~.
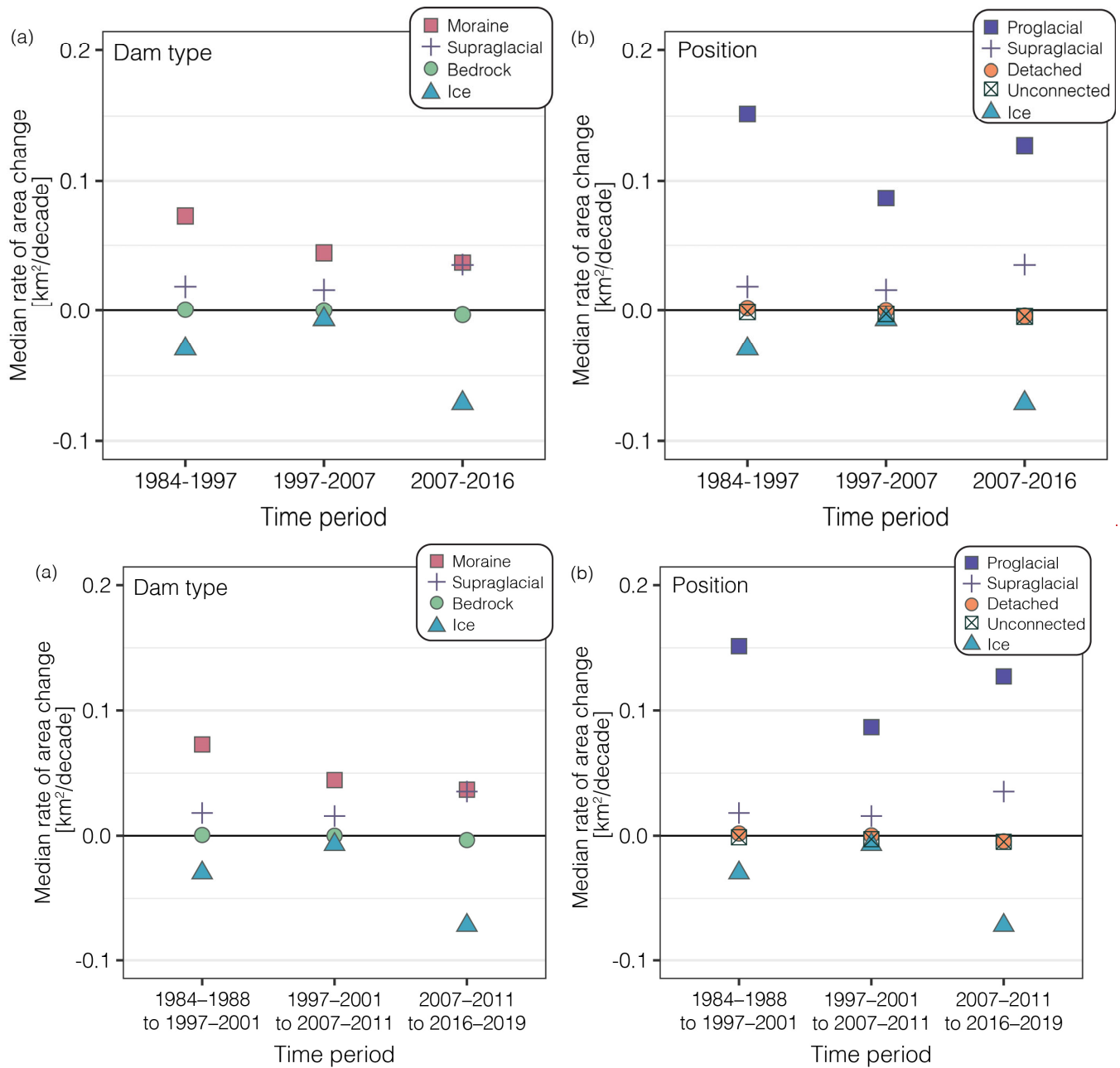
Figure 1011. Median rate of area change between each time step, categorized by dam type (a) and topological position (b).

4.4 Comparison to other regions

470

Alaska's glaciers cover a large spatial extent, spanning different climatic, geologic, and glacial environments. (Section 1). This makes the region particularly unique in ~~relating~~relation to ~~various~~other glacierized regions ~~around~~, though the ~~world.~~best analogue region depends on which Alaskan mountain range is considered. The heavily debris-covered areas (e.g., Alaska

30

Ranges) have ~~similarities~~similar debris cover to the Himalaya, areas ~~of advanced~~with clean-ice ~~glacier retreat~~valley glaciers (e.g., N Coast Ranges) ~~are more~~could behave similar to the Peruvian Andes, and the large and complex glaciers/icefields (e.g., St. Elias Mountains) ~~could relate to areas such~~have similar glacier and lake dynamics as the Patagonian Icefields. ~~Trends~~Dynamics within these Alaska subregions could ~~infer characteristics of~~shed light on ice-marginal ~~lakes~~lake behavior in comparable mountain ranges, and vice versa.

Many studies on ice-marginal lakes concentrate on High Mountain Asia (e.g., Nie et al., 2017; Zhang et al., 2018; Veh et al., 2020; Wang et al., 2020; Chen et al., 2021), a region with abundant proglacial and supraglacial lakes~~.~~, though HMA lakes tend to be smaller than Alaskan lakes (median lake area of 0.11 km^2 and 0.17 km^2, respectively; Shugar et al., 2020). Alaska and the Himalaya regions (RGI regions 14, 15) have a similar percent debris cover (~15%), though Alaska contains larger glacier and debris-covered areas (Herreid and Pellicciotti, 2020). Herreid and Pellicciotti (2020) calculated a debris stage for each RGI region from 0 to 1, where 1 indicates the ablation zone is entirely covered in debris. Debris stage is slightly higher in the Himalaya (~0.6–0.7) than Alaska (~0.5), though Alaska has a higher debris expansion potential (Herreid and Pellicciotti, 2020). This suggests that ~~as~~if debris cover expands in Alaska, these areas could become more similar to the heavily debris-covered areas in the Himalaya. Supraglacial lakes in the Himalaya vary considerably in location, shape and size, appearing, disappearing, and coalescing through time ~~(Benn et al., 2001; Gardelle et al., 2011; Nie et al., 2017), behavior exhibited in Alaska as well.~~(Benn et al., 2001; Gardelle et al., 2011; Nie et al., 2017), behavior exhibited in Alaska as well. These similarities indicate that supraglacial lakes within these two regions have similar characteristics, and that understanding one region could aid in understanding the other.

Glacierized mountain ranges around the world exhibit varying stages of glacial retreat. The Peruvian Andes are considered to be in a late stage of glacier retreat with little potential for further lake expansion, as ice generally remains in steep, high elevation ~~basins (Emmer et al., 2020). Though the Cordillera Blanca contains tropical glaciers, their topographic locations and areas mimic glaciers within the N. Coast Ranges.~~parts of the study area (Emmer et al., 2020). In Peru, glaciers have retreated far off their LIA moraines, such that the majority of proglacial lakes shifted from moraine dammed in 1948 to bedrock dammed in 2017 as glaciers retreated and exposed bedrock overdeepenings (Colonia et al., 2017; Emmer et al., 2020). Though ice remains in many main valleys in the N~~.~~ Coast Ranges, glaciers are smaller, steeper, cleaner, and less complex than other subregions in Alaska, apart from the Juneau Icefield. ~~The~~Though lakes in the N Coast Ranges are on average larger than those found in the low-latitude Andes (median lake area of 0.21 km^2 and 0.12 km^2, respectively; Shugar et al., 2020), the abundance of moraine dammed proglacial lakes and increasing proportion of bedrock dammed lakes (39% in 1984–1988 to 44% in 2016–2019) suggests the N~~.~~ Coast Ranges could ~~be following~~follow a similar trajectory as the Cordillera Blanca, ~~and therefore a continuing~~producing a shift in dominant dam type from moraine to bedrock ~~could be expected into~~in the future.

Ice-marginal lake increases have been documented throughout the world, though characteristics such as dam type, lake location, and associated glacier behavior vary widely. Examining ice-marginal lake behavior at different stages in various

mountain ranges can help predict how these lakes might ~~behave~~evolve in the future, though such analysis is outside the scope of this study.

4.5 Feedbacks on glacier mass balance

Lake geometry likely dictates the impact a proglacial lake has on glacier mass balance. Large, deep lakes can impede a glacier
510 from reaching equilibrium by holding the terminus at lake elevation until it has retreated out of the lake basin (Larsen et al., 2015). Ice-water contact can also enhance calving, resulting in mass loss and lake expansion through terminus retreat (Carrivick and Tweed, 2013). Larsen et al. (2015) found that lake-terminating glaciers in Alaska have a more negative median mass balance in coastal regions where large, proglacial lakes have developed. Lake-terminating glaciers also experienced more rapid thinning near their terminus than land-terminating glaciers, and appear to be less directly coupled to climate variations (Larsen
515 et al., 2015). In the Himalaya, lake-terminating glaciers have been linked with increased glacier mass loss through enhanced terminal retreat and surface lowering (King et al., 2019; Maurer et al., 2019), and center flow line velocities that are more than twice that of glaciers which terminate on land (Pronk et al., 2021). We therefore expect that as glaciers continue to retreat in Alaska, proglacial lake presence, formation, or detachment will influence glacier mass balance, increasing thinning and glacier velocity where lakes are present~~.~~, though variations in thinning have been observed (e.g., the Juneau and Stikine icefields;
520 Melkonian et al., 2014, 2016).

Regional glacier thinning and mass loss rates appear to mimic lake area change in parts of Alaska. The N~~.~~ Coast Ranges and St. Elias Mountains are thinning (-1.27 ± 0.11 m yr^{-1} and -1.21 ± 0.12 m yr^{-1}, respectively) and losing mass (-1.08 ± 0.09 m w.e. yr^{-1} and -1.03 ± 0.10 m w.e. yr^{-1}) at a greater rate than other subregions from 2011–2019 (Jakob et al., 2021). These regions also experienced the largest normalized lake area growth (see Sect. 4.2). The high thinning rate in the Aleutians (-0.75
525 ± 0.06 m yr^{-1}) does not appear to be reflected in the low normalized lake area growth documented in our survey. This is likely due to the fact that 60% of lakes in the Aleutians subregion are either detached or unconnected and therefore not directly influenced by glacier dynamics. The Alaska Ranges are thinning (-0.48 ± 0.06 m yr^{-1}) and losing mass (-0.41 ± 0.05 m w.e. yr^{-1}) at the lowest average rates per region (Jakob et al., 2021) likely due to extensive debris cover, and is accompanied by the lowest normalized lake area change outside the Brooks Range.

530 ### 4.6 Future change in ice-marginal lakes

As global temperatures continue to rise and glaciers thin and retreat (Zemp et al., 2019), Alaska's glaciated landscape will change, as will the nature of ice-marginal lakes. Alaskan glaciers have retreated off their LIA moraines, and therefore it is unlikely that new moraine-dammed lakes will form without a sustained period of glacial advance or surge. However, proglacial lake expansion is expected to continue as glacier retreat accommodates lake growth, dependent on basin geometry. Using the
535 Cordillera Blanca as an ~~analog~~analogue for later stages of lake development (Emmer et al., 2020), we hypothesize a future shift in new proglacial lakes to mostly bedrock dammed lakes, as glaciers retreat into higher, steeper terrain (e.g., Linsbauer

32

et al., 2016; Furian et al., 2021), though it is uncertain how long the present stage of moraine-dammed lake growth will persist before glaciers leave their terminal overdeepenings. Alaska's glacier complexity and relative abundance of ice-dammed lakes poses an interesting question as to whether these lakes will continue to drain as they have since 1970 (Wolfe et al., 2014), or whether new ice-dammed lakes will form if tributary valley ice retreats faster than main branch ice, such as has occurred in Suicide Basin since 2011 (Kienholz et al., 2020). Modeling basin geometry and future ice extent would provide insight into where ice-marginal lakes in Alaska are likely to form in the future.

4.7 Inventory challenges

Two primary challenges were encountered while creating the inventory, which should be understood before using this dataset or applying its findings. Due to the use of spectrally-based supervised classification for lake identification, only lakes that have the spectral characteristics of water appear within our inventory. This limitation results in the exclusion of some ice-dammed lakes which are either iceberg filled, or lake basins which appear dry in the five-year mosaics due to a lake that is more often drained than filled. Therefore, this inventory is a clear minimum of ice marginal lakes, with several known omitted lakes. Known lakes which were not identified in our inventory include Suicide Basin, Valdez Lake, Snow Lake, Lake Linda, and Summit Lake, all of which are ice-dammed. These lakes, which have experienced multiple drainage events (e.g., Jones and Wolken, 2019; Kienholz et al., 2020), are important for individual GLOF hazard assessments, though they have little impact (0.4% of total lake area) on our assessment of regional decadal scale lake area trends by dam type.

Dam type classification was performed using manual visual interpretation for all lakes, with the most likely dam type identified in cases that are uncertain due to poor image resolution and/or possible mixed dam types (i.e. bedrock with moraine material; Emmer et al., 2017). A shift in dam type (e.g., ice dammed to bedrock dammed) was also documented for a few lakes, particularly where a lake becomes bedrock dammed after the loss of an ice dam (e.g., Terentiev Lake which was formerly dammed by Columbia Glacier). These lakes were classified by their most recent dam type when performing analysis on change over time. The small number of cases of transitioning dam types suggests this process is not particularly important for understanding the regional scale behavior of Alaska ice-marginal lakes discussed here.

5 Conclusions

As the second largest glacierized region outside the ice sheets, characterizing Alaska's ice-marginal lakes and their evolution has important implications for glacier mass balance, ecosystem dynamics, and GLOF hazards. Varying topographic settings (valleys, cirques, debris, icefields) and a wide range of glacier complexities allow for an abundance of ice-marginal lakes of varying dam type and locationposition. Overall, ice-marginal lakes in Alaska have grown in both number (+176, 36183 lakes, 38% increase) and area (+467483 km^2, 5759% increase) between 1984–1988 and 2016–2019, however, wethough 56% of inventoried lakes did not experience detectable change. We demonstrate that lakes with different dam types and topological positions relative to their source glacier behave differently. Moraine-dammed, proglacial lakes experienced the largest growth likely due to clean-ice glacier

33

thinning and retreat, while ice-dammed lakes experienced an overall loss in both number and area, likely due to thinning or disappearance of ice dams. Our study demonstrateshighlights the need for the inclusionvalue of parsing ice marginal lakes by dam type and topological positionlocation in comprehensive regional ice-marginal lake studies, cautioning to clarify important lake dynamics that analyzing all lakes together aliases patterns exhibited by each dam type, location, or subregion. These characteristics are crucial when assessing GLOF hazard potential in mountainous regions, and time varying inventoriesobscured by coarser regional averages. A clear understanding of ice-marginalwhich lakes are growing, and which are shrinking, as quantified here in a critical classified multitemporal ice-marginal lake inventory, is a crucial first step into understanding the drivers of historic change, predicting future lake evolution-, and assessing GLOF hazard potential in icy mountainous regions.

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