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Maritime glacier retreat and terminus area change in Kenai Fjords National Park, Alaska, between 1984 and 2021

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Abstract

Glacier change in Kenai Fjords National Park in southcentral Alaska affects local terrestrial, fresh water and marine ecosystems and will likely impact ecotourism. We used Landsat 4–8 imagery from 1984 through 2021 to manually map lower glacier ice margins for 19 maritime glaciers in Kenai Fjords National Park. Of these glaciers, six are tidewater, three are lake-terminating, six are land-terminating and four terminated in more than one environment throughout the study period. We used the mapped ice margins to quantify seasonal terminus position and areal change, including distinguishing between ice loss at glacier termini and along glacier margins. Overall, 13 glaciers substantially retreated (more than 2σ), 14 lost substantial area and only two underwent both net advance and area gain. The glaciers that had insubstantial length and area changes were predominantly tidewater. Cumulatively, the lower reaches of these 19 glaciers lost 42 km^2 of ice, which was nearly evenly distributed between the terminus and the lateral margins. The rapid rate of glacier change and subsequent land cover changes are highly visible to visitors and locals at Kenai Fjords National Park, and this study quantifies those changes in terms of glacier length and area.

1. Introduction

Alaska contains 12% of the world's glacier area outside of the ice sheets (Pfeffer and others, 2014). Nearly all of Alaska's glaciers are thinning and retreating (Larsen and others, 2007, 2015; McNabb and Hock, 2014; Radić and Hock, 2014; Yang and others, 2020) at increasing rates of melt (Arendt and others, 2009; Zemp and others, 2019). Hugonnet and others (2021) determined that, between 2000 and 2019, Alaska's glaciers lost 66.7 Gt a^{-1} or 25% of global glacier mass loss outside of ice sheets, constituting the greatest regional glacier mass loss in the world. Most of Alaska's glaciers are located along the state's southcentral and southeastern coastline between latitudes 56° and 62°N in the Pacific coastal temperate rainforest. This coastline frames the northern shores of the biologically productive Gulf of Alaska and is experiencing some of the highest rates of glacier mass loss on Earth (Gardner and others, 2013; O'Neel and others, 2015). Although all mountain glaciers make up a small percentage of global glacier area when compared to Antarctica and Greenland, their melt rate contributes approximately half of all glacier meltwater to sea-level rise (Gardner and others, 2013; Wouters and others, 2019; Zemp and others, 2019).

Glacier mass loss results in a reduction of glacier ice which appears on the landscape as a decrease in surface elevation (thinning) or a decrease in a glacier's area and length (retreating). The change in glacier area results in a reconfiguration of land cover; areas previously covered by ice are replaced with a different surface type. Tidewater glacier retreat allows marine waters to flood in their wake, creating or elongating a fjord. With continuous retreat they may eventually exit the water and become land-terminating glaciers. When land-terminating glaciers retreat, they leave behind lakes, rivers or freshly disturbed terrain that will be colonized and eventually vegetated. The retreat of lake-terminating glaciers results in the expansion of the lake and, once they retreat onto land, terrestrial disturbance. In each case, the land cover mosaic and each associated habitat change from ice to marine water, fresh water or terrestrial vegetation. It is imperative for land management agencies such as the U.S. National Park Service to know the land cover within and around their boundaries for effective management. National parks with glaciers and glacier-affected areas preserve the aesthetic (scenic), cultural, ecological, educational, recreational and touristic values embodied by glaciers (Capps, 2017).

Most of Alaska's temperate rainforest coastline is dominated by mountains and fjords (Nowacki and others, 2003; Bidlack and others, 2021). Perennial snow and ice cover 17% of the coastal landscape rimming the northern Gulf of Alaska (Beamer and others, 2016) including land-terminating, lake-terminating and tidewater glaciers. Active tidewater glacier fjords are unique ecosystems that occur in high-latitude coastal environments in Alaska, Antarctica, the Canadian Arctic, Russian Arctic, Greenland, Chile, Iceland and Svalbard (Bianchi and others, 2020). The Kenai Fjords, located on the Kenai Peninsula in Southcentral Alaska (Fig. 1), were carved by glaciers flowing east from the Harding Icefield, a 2080 km^2 icefield (Loso and others, 2014). Today only three of the fjords have active

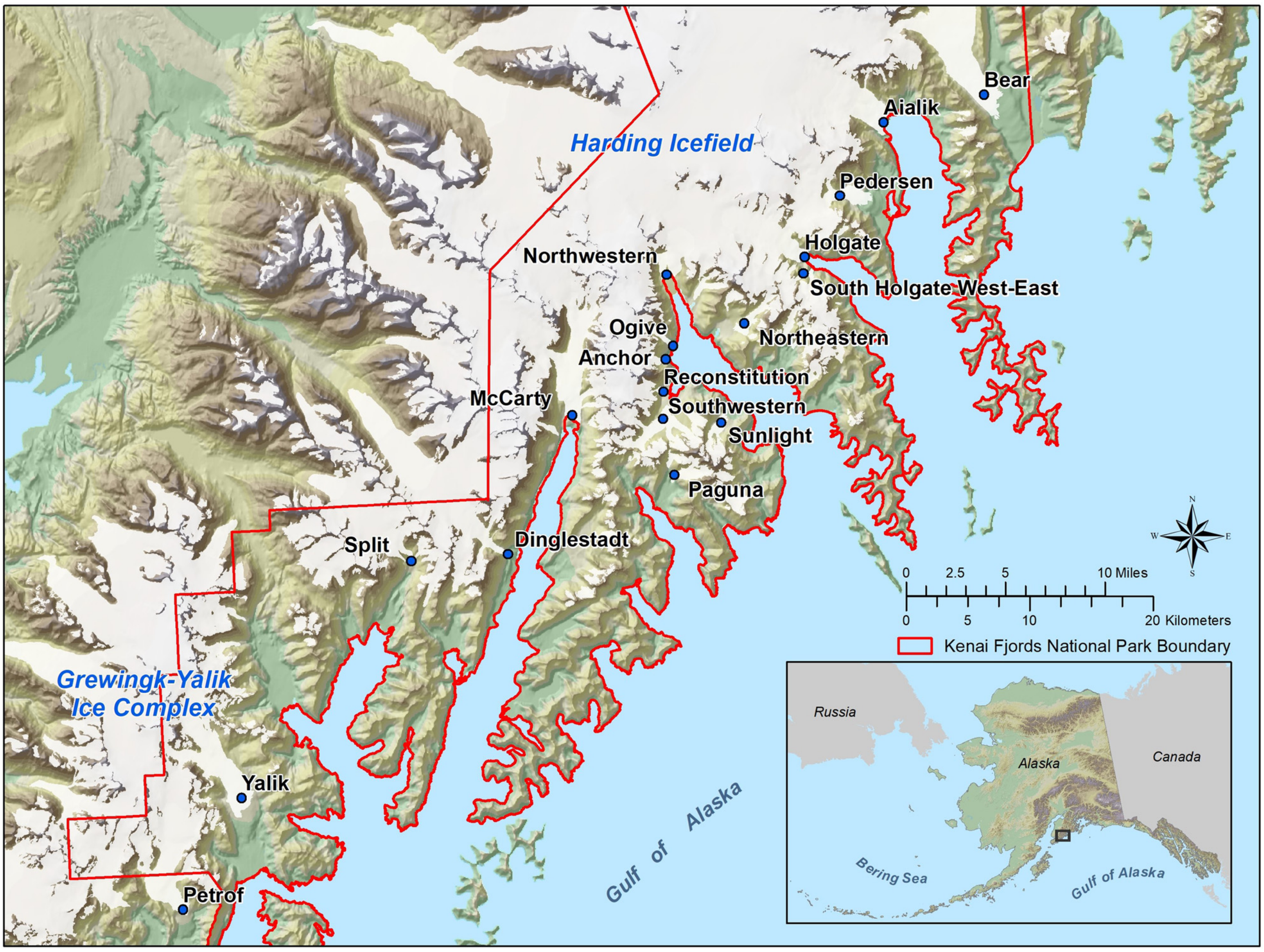

Fig. 1. Overview map of all glaciers in study area (blue points) with each glacier's name, the Kenai Fjords National Park boundary in red, and an inset indicating the location of the study area.

tidewater glaciers. Land-terminating and lake-terminating glaciers are also present along the coast; some continue to flow outward from the Harding Icefield while others are now disconnected from the icefield. Alaska's maritime glaciers are strongly influenced by their proximity to the northeast Pacific Ocean and its relatively warm, wet climate (Josberger and others, 2007). As the climate changes, it will affect glacier mass balance as increasing temperatures increase surface ablation (Larsen and others, 2015; O'Neel and others, 2019) and the changing quantity and phase of precipitation affect winter snow accumulation (O'Neel and others, 2019; Hugonnet and others, 2021). All glacier types are sensitive to climate change, but tidewater glaciers tend to be more dynamic as they respond to both climate forcing and fjord geometry (Post and others, 2011), resulting in a pattern of advance and retreat known as the tidewater glacier cycle (Trabant and others, 1991). While several Alaskan tidewater glaciers have recently advanced (Ritchie and others, 2008; Truffer and others, 2009; McNabb and Hock, 2014), climate change is overriding the tidewater cycle and most tidewater glaciers in Alaska and around the world are retreating (Arendt and others, 2002; Larsen and others, 2007; McNabb and Hock, 2014; Wouters and others, 2019; Zemp and others, 2019; King and others, 2020). These tidewater glaciers are predicted to continue retreating (Hock and others, 2019; Slater and others, 2019), with consequent contributions to sea level rise (Arendt and others, 2002; Gardner and others, 2013; Huss and Hock, 2015) and marine ecosystems (Lydersen and others, 2014; O'Neel and others, 2015; Arimitsu and others, 2016; Hoover-Miller and Armato, 2018).

The Harding Icefield has been the focus of numerous glacier change studies, including quantification of changes to areal extent (Wiles and Calkin, 1994; Wiles and others, 1995; Giffen and others, 2014; Loso and others, 2014), Holocene and modern terminus retreat (Barclay and others, 2009; Kurtz and Baker, 2016), surface elevation (Adalgeirsdóttir and others, 1998; Sapiano and others, 1998; Arendt and others, 2002; Echelmeyer and others, 2002; VanLooy and others, 2006; Loso and others, 2014; Larsen and others, 2015), mass balance (Kurtz, report in preparation) and estimates of the magnitude and timing of seasonal terminus variations of tidewater glaciers (McNabb and Hock, 2014). Results of these studies conclude that the icefield is shrinking and the rate of areal loss is increasing.

Here we map lower glacier ice margins for 19 maritime glaciers in the Kenai Fjords to quantify nearly four decades of seasonal areal and terminus position change. The selected glaciers include tidewater, lake-terminating and land-terminating glaciers. We chose these 19 glaciers due to their various stages of retreat from the marine environment, their role in proglacial lake and river development and/or their status as a tourist attraction for visitors to Kenai Fjords National Park. Mapping glacier outlines from satellite imagery provides historical context for glacier area and length change and gives information about changes to land cover and habitat. Although the processes that influence glacier area and length also drive changes to glacier mass, we do not intend to use our measurements as a proxy for mass balance, as glacier area and length changes are influenced

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by, but do not necessarily correspond to glacier mass change (Roe, 2011; O'Neel and others, 2019). However, changes to a glacier's geometry due to surface melt and areal change contribute to mass-balance changes, while long-term negative mass-balance measurements result in changes in glacier length and area.

2. Study area

The Harding Icefield is situated in the Kenai Mountains between latitudes 59.5° and 60.3°N on the southern portion of the Kenai Peninsula in southcentral Alaska (Fig. 1). The glaciers that make up the Harding Icefield flow outward in all directions from the central plateau, terminating on land, in lakes or, on the southeastern part of the icefield, into the marine environment of the Kenai Fjords. The fjords are located along the northwestern coast of the Gulf of Alaska in the Northern Pacific Ocean, an area known for its marine wildlife and dramatic scenery. Management of the Harding Icefield falls under the jurisdiction of the Kenai National Wildlife Refuge to the west and Kenai Fjords National Park to the east. The area currently managed by Kenai Fjords National Park is within the ancestral lands of the Alutiiq or Sugpiaq people, many of whom now reside in the Alaska Native villages of Port Graham and Nanwalek on the southwest corner of the Kenai Peninsula. Glaciers, specifically the tidewater glaciers, are one of the main features that draw visitors to the Kenai Fjords. In 2018, tour boat companies reported that nearly 123 000 people travelled into the fjords on tour boats and viewed the park's maritime glaciers.

3. Data and methods

We manually digitized lower glacier outlines for 19 maritime glaciers in Kenai Fjords National Park (Fig. 1) using available spring and autumn Landsat 4–8 images between 1984 and 2021. Geographic details about each glacier are provided in Table 1. We used the manually digitized glacier outlines and additional reference features for each glacier to measure their area and length and determine changes in size over the observational period. We also visited most of the study glaciers in the spring and summer of 2021 and made additional observations about current conditions that were difficult to discern in satellite images. Except for Petrof Glacier, all of the glaciers in this study are documented by the park's repeat photo collection, which is updated annually. The collection is archived at the park and as a special photo collection at the National Snow and Ice Data Center's Glacier Photo Collection (National Snow and Ice Data Center, 2021).

3.1. Data acquisition

For each glacier, we created the following static features: (1) a point marking the glacier centroid location; (2) a centerline from the Randolph Glacier Inventory (RGI Consortium, 2014), modified as needed to extend to the maximum observed length of the glacier (Fig. 2a); (3) a reference box, with one side drawn perpendicular to glacier flow and down-glacier of any tributary glaciers connecting to the main trunk, two additional lines extending laterally along the glacier edges past the terminus and open-ended in the down-flow direction (Fig. 2b); and (4) a reference line (or 'gate') with which to intersect each digitized glacier outline, equivalent to the back end of the reference box but extended beyond the full width of the glacier (Fig. 2c). Each of these features was stored within a corresponding feature class in an ESRI File Geodatabase.

We used spring and autumn Landsat images to study long-term glacier change in Kenai Fjords National Park. We limited our image search to spring (May and June) and autumn (mid-August through mid-October) to approximately capture the seasonal maximum and minimum extents of the glaciers. Additionally, because repeat mapping of glacier features requires high geometric precision, we included only images with Landsat's Tier 1 (T1) and Level-1 Precision and Terrain (L1TP) classifications, which meet Landsat's highest geometric precision standards. While this selection ensures high geometric precision within a given Landsat scene coordinate, we observed that the geometric precision between overlapping scene coordinates was inconsistent. Therefore, we limited our image search to scene coordinate 069/018 (under the Worldwide Reference System-2 (WRS-2) path/row notation), which fully covers the glaciers of interest in this study. The WRS-2 was first used with Landsat-4, launched in 1982. Prior to Landsat-4, the Landsat series used the WRS-1 system. The WRS-1 scene coordinate 074/018 covers our glaciers of interest; however, we found no images at this coordinate that satisfied the T1 and L1TP criteria. Therefore, the earliest potential year from which we could acquire images was 1982.

With these constraints in mind, we searched the Landsat Public Data on Google Cloud Platform for all Landsat product identification numbers that met these requirements and downloaded all resulting images. All images were re-projected into the NAD83(2011)/Alaska Albers coordinate reference system (EPSG:6393), the standard system used by the NPS Alaska region, including Kenai Fjords National Park. The red, green and blue bands were combined to create a true-color composite for each image. Finally, for Landsat-7 and Landsat-8, the color composite image was pan-sharpened using the panchromatic band. This process yielded over 200 true-color image candidates at 15–30 m resolution.

3.2. Glacier outline digitization

For each glacier, we reviewed the candidate images and manually digitized the glacier outline down-glacier of its reference line, once during each season in which the outline was clearly visible. Our digitization approach differs from that of most ice margin data submitted to the Randolph Glacier Inventory (RGI Consortium, 2014) in that we digitized manually rather than through an automated process, we included some ground-truthing of glacier positions and we did not digitize the entire ice margin. We discarded all images in which the Landsat-7 scan-line corrector failure 'stripes' were present and passed over images in which the glacier was obscured by clouds. For spring outlines, we prioritized May images, and used June images when none from May were available. For autumn outlines, we prioritized September images, and used images from 17–31 August or 1–16 October when none from September were available. In the few cases where there were two viable images over a glacier in one season, we used the image in which the glacier outline was clearest (e.g. higher contrast or fewer clouds). In cases where there were no viable images available within our defined seasons, we did not record any data.

We included metadata with the glacier outlines to assist data analysis and to ensure reproducibility. After digitizing a glacier outline, we noted the current termination type (land, lake or tidewater), the Landsat Product ID of the image used for digitization and a quality flag for the outline. The quality flag indicates whether the analyst was certain or uncertain about the accuracy of the outline, and was subjectively assigned. Uncertainty flags were typically due to image saturation or features that hindered interpretation, such as shadows, snow or debris cover, or scattered clouds. Additional attributes, such as the image date and associated season, were automatically generated based on the Landsat Product ID.

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Table 1. Reference information including official or unofficial name, termination type, GLIMS ID number, centroid coordinates and length and area from the Randolph Glacier Inventory (RGI) v6.0 for each glacier in the study area

Name	Termination type	GLIMS ID	Centroid coordinates	RGI area (km^2)	RGI length (km)
Bear Glacier[a]	Lake	G210235E60050N	60.04°N, 149.72°W	198.091	36.6
Aialik Glacier[a]	Tidewater	G210091E59984N	59.97°N, 149.84°W	141.533	19.206
Pedersen Glacier[a]	Lake	G210146E59907N	59.91°N, 149.85°W	31.634	11.409
Holgate Glacier[a]	Tidewater	G210021E59901N	59.89°N, 149.98°W	97.125	24.303
South Holgate Glacier – West[b]	Land	G210103E59831N	59.83°N, 149.90°W	2.626	3.494
South Holgate Glacier – East[b]	Tidewater/land	G210135E59826N	59.83°N, 149.86°W	5.463	3.878
Northeastern Glacier	Land	G210061E59818N	59.82°N, 149.94°W	5.396	6.03
Northwestern Glacier[a]	Tidewater	G209902E59882N	59.88°N, 150.07°W	50.299	15.184
Ogive Glacier	Tidewater	G209874E59806N	59.80°N, 150.09°W	7.501	6.706
Anchor Glacier	Tidewater	G209874E59787N	59.80°N, 150.13°W	6.867	5.326
Reconstitution Glacier	Tidewater/land	G209876E59766N	59.76°N, 150.09°W	4.905	4.981
Southwestern Glacier	Land/lake	G209894E59736N	59.74°N, 150.10°W	14.597	7.008
Sunlight Glacier	Land	G209989E59718N	59.73°N, 150.02°W	3.687	4.806
Paguna Glacier	Land	G209947E59704N	59.70°N, 150.05°W	3.239	3.909
McCarty Glacier[a]	Tidewater	G209749E59808N	59.80°N, 150.25°W	110.053	19.124
Dinglestadt Glacier[a]	Land	G209617E59675N	59.67°N, 150.38°W	24.315	9.681
Split Glacier[a]	Land	G209508E59678N	59.68°N, 150.50°W	12.422	7.077
Yalik Glacier[a]	Lake	G209214E59535N	59.53°N, 150.78°W	41.538	15.254
Petrof Glacier[a]	Lake/land	G209166E59462N	59.46°N, 150.83°W	43.424	15.126

[a]Indicates official name designated by the US Board on Geographic Names.
[b]South Holgate Glacier – West/East are also known together as Surprise Glacier or Little Holgate Glacier.

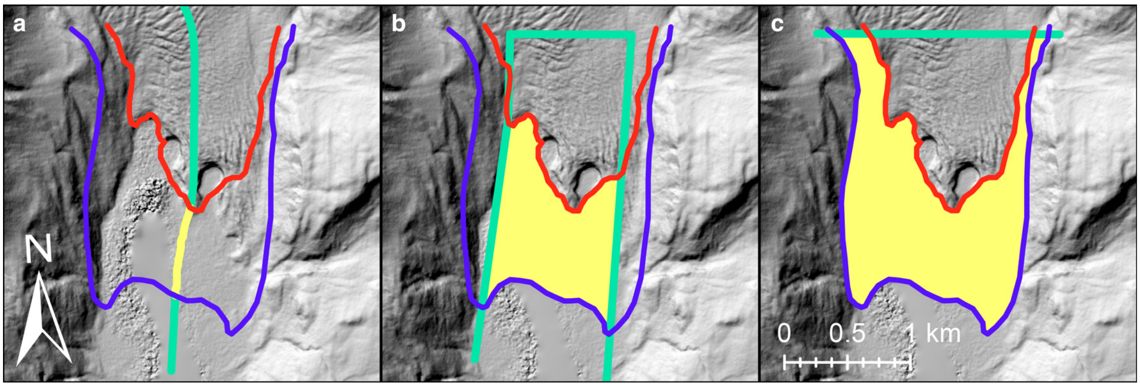

Fig. 2. Illustration of the (a) centerline method, (b) box method and (c) outline method for measuring glacier change, using McCarty Glacier as an example. Glacier outlines are shown in purple (1984-06-18) and red (2020-09-09). The centerline (a), reference box (b) and reference line (c) are shown in green. Change measurements (a) along the centerline, (b) within the reference box and (c) beyond the reference line are shown in yellow. The base image is a hillshade of a DEM derived from a US Fish and Wildlife Service-led structure-from-motion data acquisition in 2016.

3.3. Glacier change measurements

We measured the length and lower glacier area change of each glacier between each observation using, respectively, the centerline method and the box method (Moon and Joughin, 2008) and a variant which we term the outline method, which allows us to distinguish terminus retreat from total area loss. To determine glacier length, we measured from the up-glacier end of the centerline to where it intersects with the glacier outline (Fig. 2a). The change in centerline length between observations approximates the length of glacier retreat and advance over time. To determine glacier area with the box method, we intersect a glacier's reference box, which contains the main body of the glacier, with a glacier outline to create a polygon (Fig. 2b); we refer to this as the 'terminus area'. While the area of this polygon is arbitrary, depending on how the reference box is drawn, the change in area between observations represents the change in ice area at the glacier terminus. The outline method is conceptually similar to the box method, but we instead intersect the glacier outline with a straight reference line, which we chose to be coincident with the up-glacier edge of the glacier reference box to allow direct comparison between the two methods (Fig. 2c); we refer to this as the 'lower glacier area'. The change in area of this polygon between observations represents the total change in ice area – both laterally and at the terminus – down-glacier of the reference line. Therefore, the difference between the area changes as measured by the box and outline methods is approximately equivalent to the area change along the glacier sides, i.e. narrowing or widening as glacier width changes. We use both the box method and the outline method because glacier area change does not necessarily occur solely at the terminus, and similarly, changes at the terminus do not necessarily correspond to area changes elsewhere on the glacier. After creating time series of glacier length and area changes, we calculated whether the net change exceeds two standard deviations (2σ) of the data, and used this threshold to define 'substantial' glacier change over our observation period.

3.4. Seasonal variability

Although we attempted to measure each glacier in both spring and autumn annually, cloud cover, particularly for the spring images, and lack of imagery prevented us from creating a complete continuous time series at this temporal resolution. To assess seasonal changes in length, we filtered each glacier's time series down to only continuous spring-to-autumn (summer) and autumn-to-spring (winter) measurements. We differenced these measurements (i.e. measured the advance or retreat from one

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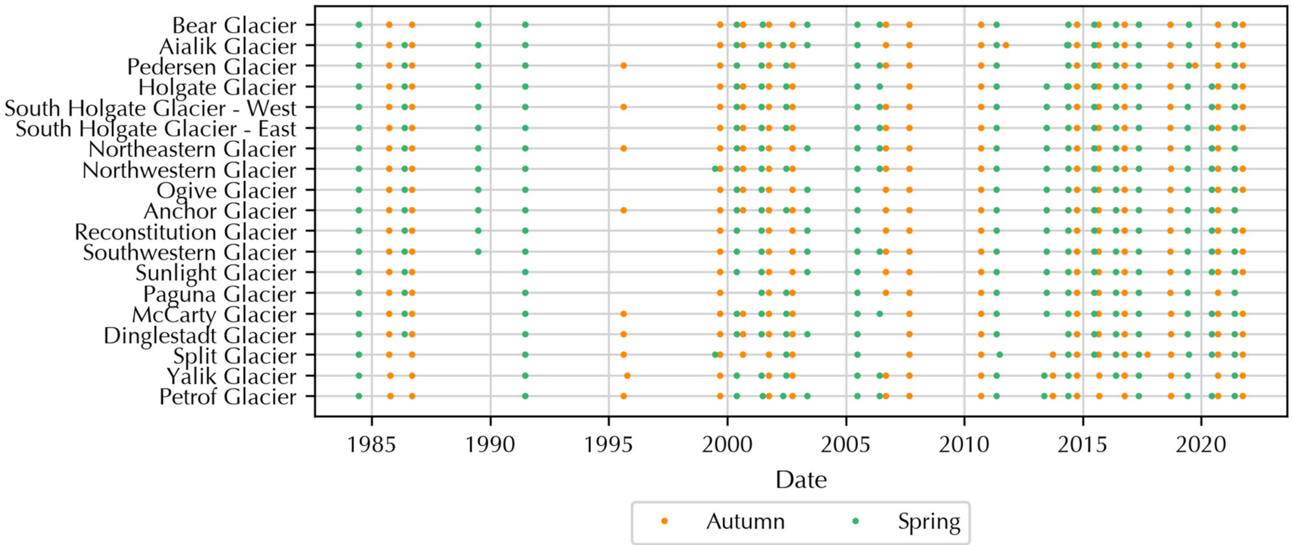

Fig. 3. Time series of individual seasonal observations for each glacier.

season to the next) and found the median values of the difference for spring and autumn measurements. For example, if a glacier typically advanced from autumn to spring, its median difference value for spring would be positive. We did not assess seasonal changes in area because the timing of end-of-winter seasonal snow cover and/or avalanche debris along the margins varies annually, and so the ability to accurately delineate ice margins (and thus calculate lower glacier area) was often hindered. This potential uncertainty in our spring area measurements could bias the seasonal area difference results.

3.5. Measurement uncertainty

Several factors may introduce uncertainty into our measurements. The lateral margins of glaciers were often more difficult to accurately digitize than termini due to marginal avalanche and landslide deposits, more extensive spring snow cover at higher elevations, and difficulty distinguishing supraglacial debris cover from lateral moraines. While calving glacier termini can also be difficult to digitize due to difficulty distinguishing glacier ice from mélange, sea ice or lake ice, we did not encounter these complications with the images that we used. Therefore, the measurements derived from the outline method may have a greater uncertainty than those from the box method (i.e. the terminus area change measurements). A single analyst traced all glacier outlines to minimize potential uncertainty introduced by differing interpretations of features such as snow cover and moraines. We do not expect that any error introduced by these potential sources of image misinterpretation is significant enough to obscure the overall trends in area change. We retained both the box and outline methods to provide multiple metrics for understanding trends in glacier change. The centerline method for measuring glacier length ideally represents the maximum extent of the glacier at the time of that observation. However, it may underestimate the maximum length if the terminus shape is concave, lopsided or variable. All these methods measure changes in the surface extent of glaciers, and we do not extend these measurements to estimate volumetric changes.

4. Results

We digitized seasonal glacier outlines (spring and autumn) for 40 seasons between spring of 1984 and autumn of 2021, using 50 different Landsat images (Fig. 3). Most observations were after the year 2000 due to limitations of available and viable imagery; there was a dearth of observations in the 1990s and scattered observations in the 1980s. Overall, we digitized an average of 32 outlines per glacier between 1984 and 2021 (Fig. 4).

Between 1984 and 2021, the glaciers in our study cumulatively lost ~42 km^2 of lower glacier ice area (using the outline method), which was partitioned as ~24 km^2 at their termini (using the box method) and ~18 km^2 along their lateral margins (from differencing the outline and box methods). Of the 19 glaciers we examined, only two (Holgate and Paguna) underwent both net centerline advance and net area gain over the course of the study period. We also detected insubstantial centerline advance at Ogive Glacier. The net changes in centerline length, lower glacier area and terminus area for individual glaciers are detailed in Table 2 and illustrated in the Supplementary Figures. The decadal rates of areal change and centerline length change are detailed in Supplementary Tables S1 and S2, respectively. When seasonal measurements were continuous, we found that most glaciers tended to retreat through the summer (between spring and autumn observations), while winter behavior (between autumn and spring observations) was more variable (Table 3). Below we group the glaciers into different termination types primarily to isolate the tidewater glaciers, which are influenced by processes occurring at the ice-marine interface in addition to climate change (Trabant and others, 1991). The termination types are also indicative of the proglacial habitats that are vulnerable to change as the glacier retreats. Specifically, tidewater glaciers influence marine ecosystems, lake-terminating glaciers influence fresh water lakes and associated stream outlets and land-terminating glaciers affect freshwater riverine and terrestrial habitats.

4.1. Tidewater glaciers

Six glaciers were tidewater for the duration of the study period: Aialik Glacier, Holgate Glacier, Northwestern Glacier, Ogive Glacier, Anchor Glacier and McCarty Glacier. Each of these glaciers experienced net growth and centerline advance between 1986 and 1990, and net loss and centerline retreat between 1990 and 1999 (note that we only have 2–3 observations in the 1990s for most of these glaciers, so we cannot define this retreat period more precisely), after which their individual behaviors became more variable (Figs 5a, b). The majority of the measured area change in the lower glacier was at the terminus for all tidewater glaciers except Aialik and Anchor Glaciers, which

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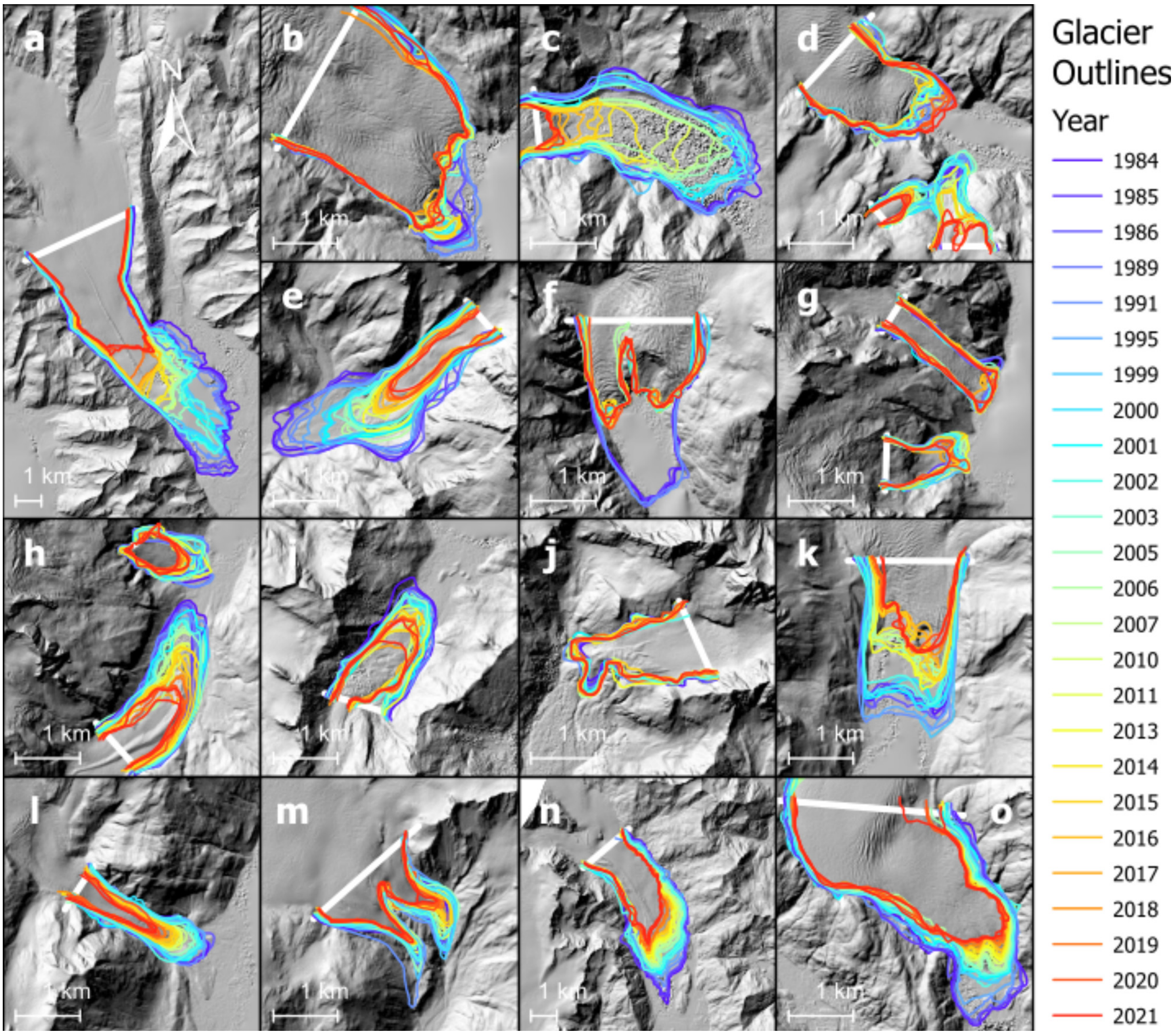

Fig. 4. Maps of all seasonal outlines traced for (a) Bear Glacier; (b) Aialik Glacier; (c) Pedersen Glacier; (d) Holgate Glacier (top), South Holgate Glacier – West (bottom left) and South Holgate Glacier – East (bottom right); (e) Northeastern Glacier; (f) Northwestern Glacier; (g) Ogive Glacier (top) and Anchor Glacier (bottom); (h) Reconstitution Glacier (top) and Southwestern Glacier (bottom); (i) Sunlight Glacier; (j) Paguna Glacier; (k) McCarty Glacier; (l) Dinglestadt Glacier; (m) Split Glacier; (n) Yalik Glacier; and (o) Petrof Glacier. The color scale ranges from purple as the oldest (1984) to red as the youngest (2021). Glacier reference lines are shown in white. Maps (a) and (n) are shown at 1:250 000 scale, and all others are at 1:100 000 scale. The base image is a hillshade of a DEM from a US Fish and Wildlife Service-led structure-from-motion data acquisition in 2016.

experienced the majority of their area change in the lower glacier along their margins. When seasonal measurements were continuous, they indicated that all of these tidewater glaciers tended to retreat in the summer and advance in the winter. However, in most cases the median seasonal advance or retreat was less than the typical image resolution (15 m for most of the continuous measurements), and so could be difficult to detect in satellite images. The exceptions to this resolution limit were Aialik and Holgate Glaciers (in winter), and McCarty Glacier (in both summer and winter).

Aialik Glacier (net centerline length change −0.01 km, net lower glacier area change −0.60 km^2) was stable at the terminus centerline from 2000 through 2021, after advancing and then retreating ∼600 m in the late 1980s and 1990s, respectively. The glacier continued losing ice area laterally for nearly two decades while the terminus was stable. The lateral loss is almost entirely restricted to the northeastern margin of the glacier. Despite the concentrated area loss along part of the terminus, neither the length change, lower glacier area change, nor terminus area change at Aialik Glacier qualified as substantial (>2σ).

Holgate Glacier (+0.47 km, +0.22 km^2) had cycles of advance and retreat between 1984 and 2021 and was the only tidewater glacier that substantially gained both terminus area and length since the beginning of the observation period in 1984 (lower glacier area change was insubstantial). Nearly all area gained was at the terminus, suggesting that the glacier did not widen as it advanced.

Northwestern Glacier (−1.59 km, −1.63 km^2) retreated in the 1990s and was relatively stable between ∼1999 and 2021. The centerline length, lower glacier area and terminus area changes were all substantial.

Ogive Glacier (+0.49 km, −0.07 km^2) may have had multiple periods of small-magnitude advance and retreat at the centerline between 1984 and 2021. It experienced insubstantial lower glacier area loss, as well as insubstantial advance and terminus area gain. However, the glacier front is small and debris-covered, making it difficult to distinguish the sediment-laden ice from the adjacent unconsolidated material in satellite images. Therefore, Ogive Glacier's area and length measurements may be subject to more error than the measurements for other glaciers. Due to the

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Table 2. Net centerline length change (ΔL), net lower glacier area change (ΔA) and net terminus area change (excluding lateral changes; ΔA_{term}) for each glacier from 1984 to 2021

Glacier	Net ΔL (km)	Net ΔA (km^2)	Net ΔA_{term} (km^2)
Bear Glacier	**−5.17** (3.08)	**−17.28** (9.55)	**−10.83** (6.56)
Aialik Glacier	−0.01 (0.33)	−0.60 (0.77)	−0.29 (0.36)
Pedersen Glacier	**−3.19** (2.65)	**−4.25** (3.14)	**−1.71** (1.34)
Holgate Glacier	**+0.47** (0.30)	+0.22 (0.30)	**+0.24** (0.17)
South Holgate Glacier – West	**−0.39** (0.22)	**−0.21** (0.15)	**−0.08** (0.06)
South Holgate Glacier – East	**−1.26** (0.92)	**−0.47** (0.40)	**−0.28** (0.23)
Northeastern Glacier	**−2.07** (1.26)	**−2.43** (1.58)	**−1.05** (0.64)
Northwestern Glacier	**−1.59** (1.20)	**−1.63** (1.28)	**−1.40** (1.09)
Ogive Glacier	+0.49 (0.08)	−0.07 (0.09)	+0.01 (0.05)
Anchor Glacier	−0.12 (0.27)	−0.12 (0.17)	−0.05 (0.09)
Reconstitution Glacier	**−0.31** (0.29)	**−0.42** (0.28)	**−0.42** (0.28)
Southwestern Glacier	**−1.55** (0.88)	**−1.38** (0.89)	**−0.55** (0.39)
Sunlight Glacier	**−0.61** (0.50)	**−0.91** (0.60)	**−0.27** (0.17)
Paguna Glacier	**+0.21** (0.13)	−0.03 (0.12)	**+0.12** (0.08)
McCarty Glacier	−0.75 (0.75)	**−1.84** (1.54)	**−0.96** (0.91)
Dinglestadt Glacier	**−0.90** (0.55)	**−0.75** (0.52)	**−0.37** (0.23)
Split Glacier	**−0.55** (0.49)	**−0.68** (0.53)	**−0.46** (0.40)
Yalik Glacier	**−2.27** (1.24)	**−6.92** (3.97)	**−5.07** (2.87)
Petrof Glacier	**−1.03** (0.57)	**−2.33** (1.33)	**−1.06** (0.69)

Substantial (>2σ) values are indicated by bold type, and the 2σ values are given in parentheses.

Table 3. Median difference between consecutive spring-to-autumn (i.e. summer) and autumn-to-spring (i.e. winter) centerline length measurements for each glacier

Glacier	Median summer length change (m)	Median winter length change (m)
Bear Glacier	**−16** (n = 7)	−10 (n = 9)
Aialik Glacier	−4 (n = 9)	**24** (n = 11)
Pedersen Glacier	−11 (n = 9)	**−34** (n = 9)
Holgate Glacier	−11 (n = 9)	**21** (n = 10)
South Holgate Glacier – West	**−19** (n = 10)	10 (n = 10)
South Holgate Glacier – East	**−24** (n = 10)	6 (n = 10)
Northeastern Glacier	**−22** (n = 8)	**−21** (n = 10)
Northwestern Glacier	−1 (n = 11)	4 (n = 10)
Ogive Glacier	−11 (n = 8)	12 (n = 10)
Anchor Glacier	−1 (n = 8)	9 (n = 11)
Reconstitution Glacier	**24** (n = 7)	**−28** (n = 9)
Southwestern Glacier	**−76** (n = 8)	**18** (n = 9)
Sunlight Glacier	**−23** (n = 7)	**23** (n = 9)
Paguna Glacier	6 (n = 6)	−3 (n = 8)
McCarty Glacier	**−68** (n = 9)	**56** (n = 10)
Dinglestadt Glacier	**−32** (n = 9)	−3 (n = 11)
Split Glacier	**−27** (n = 8)	**15** (n = 8)
Yalik Glacier	**−81** (n = 7)	−5 (n = 8)
Petrof Glacier	−13 (n = 7)	−11 (n = 8)

Values greater than the typical image resolution (~15 m) are indicated by bold type.

small absolute magnitudes of measured advance and retreat, we cannot confidently disentangle this imprecision from the glacier's true behavior. In 2021, Ogive Glacier terminated in the tidal zone, where it lost contact with marine waters during low tides.

Anchor Glacier (−0.12 km, −0.12 km^2) experienced cycles of advance and retreat at the centerline including an advance from 2017 through 2020. Overall, it experienced a net lower glacier area loss between 1984 and 2021, including a small decrease in area at the terminus. This indicated that the glacier is continuing to lose ice along the margins despite its recent advance, although neither the net area changes nor the centerline length change were substantial. Recent areal gains at the terminus were likely the result of icefall and avalanche debris reconstituting the lower glacier area.

McCarty Glacier (−0.75 km, −1.84 km^2) has undergone periods of advance, stability and retreat, resulting in a net loss of centerline length and area between 1984 and 2021. Although the length change was insubstantial, the lower glacier and terminus area changes were substantial.

4.2. Lake-terminating glaciers

Three glaciers were lake-terminating for the duration of the study period: Bear Glacier, Pedersen Glacier and Yalik Glacier. These glaciers experienced the greatest magnitudes of centerline retreat and lower glacier and terminus area losses of all glaciers in the study area (Figs 5c, d). These glaciers also retreated continually throughout the duration of the study period, with no notable observed advances. At Bear and Yalik Glaciers, the majority of area loss in the lower glacier was at the terminus, while at Pedersen Glacier the majority of area loss in the lower glacier was along the margins. Retreat of these glaciers corresponded with growth of their proglacial lakes. Continuous seasonal measurements indicated that all three of these glaciers tended to retreat during both the summer and the winter. These seasonal changes were greater than the typical image resolution in the summer at Bear and Yalik Glaciers, and in the winter at Pedersen Glacier.

Bear Glacier (−5.17 km, −17.28 km^2) lost substantial centerline length and lower glacier and terminus area between 1984 and 2021, with periods of accelerated retreat between 2014 and 2016 and between 2018 and 2021.

Pedersen Glacier (−3.19 km, −4.25 km^2) lost substantial centerline length and lower glacier and terminus area between 1984 and 2021. The glacier advanced ~100 m along its centerline between 1984 and 1991, but then retreated at an increased decadal rate until 2016 when the retreat rate rapidly decelerated, and the terminus has remained nearly stable through 2021.

Yalik Glacier (−2.27 km, −6.92 km^2) lost substantial centerline length and lower glacier and terminus area between 1984 and 2021. Over half of the terminus rested on a terminal moraine from ~2005 through 2017.

4.3. Land-terminating glaciers

Six glaciers were land-terminating for the duration of the study period: South Holgate Glacier – West, Northeastern Glacier, Sunlight Glacier, Paguna Glacier, Dinglestadt Glacier and Split Glacier. During the Little Ice Age, South Holgate – West, Northeastern, Sunlight and Dinglestadt Glaciers were tidewater glaciers, or tributaries thereof, and retreated onto land sometime before our study period (Grant and Higgins, 1913; Wiles and others, 1995; Calkin and others, 2001). We did not find any references indicating whether Paguna Glacier and Split Glacier were tidewater or tidewater glacier tributaries during the Little Ice Age. Most of these glaciers experienced net centerline retreat at rates following an overall decreasing trend, except for Paguna Glacier, which continuously advanced from at least 1984 until ~2007 when its terminus position became stationary (Figs 5e, f). Both Paguna Glacier and Sunlight Glacier are partially covered with debris from landslides related to the M9.2 Alaska Earthquake that occurred in 1964 (Post, 1967). All of these glaciers had persistent proglacial stream systems visible in satellite imagery throughout the study period. In particular, Dinglestadt and Split Glaciers' stream systems appeared to have active deltas that produced large sediment plumes in their respective fjords. Dinglestadt and Split Glaciers, as well as South Holgate Glacier – West, also experienced the majority of their measured lower glacier area loss at the terminus, while the other three glaciers experienced the majority of their area loss in the lower glacier along their margins. Continuous seasonal measurements indicated that these land-terminating glaciers tended to retreat during the summer and that this retreat was

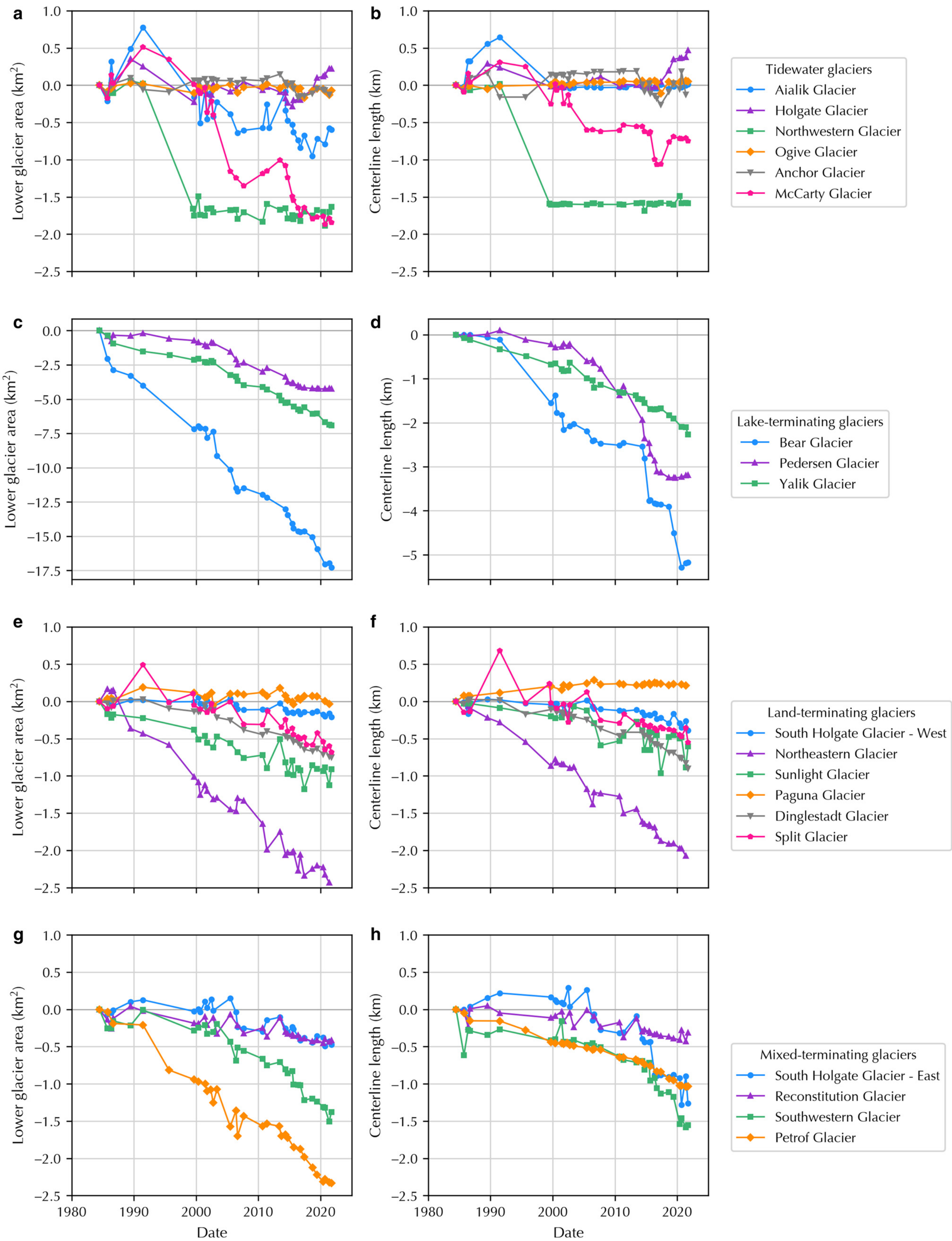

Fig. 5. Summary of observed (left column) lower glacier area and (right column) centerline length changes for (a, b) tidewater glaciers, (c, d) lake-terminating glaciers, (e, f) land-terminating glaciers and (g, h) mixed-terminating glaciers. Note that the vertical scale is the same for all plots except the lake-terminating glaciers (c, d).

greater than the typical image resolution, except at Paguna Glacier, which tended to have advanced below the typical image resolution. Winter behavior was more variable, with Northeastern, Paguna and Dinglestadt Glaciers tending to retreat, and South Holgate – West, Sunlight and Split Glaciers tending to advance. In the winter, only the retreat at Northeastern Glacier

and the advance at Sunlight Glacier were greater than the typical image resolution.

South Holgate Glacier – West (−0.39 km, −0.21 km^2) substantially retreated along its centerline and lost lower glacier and terminus area from the late 1980s through 2021. Small, ephemeral lakes visible in Landsat imagery may have been present at or near the terminus in 2014, 2015 and 2020. South Holgate Glacier – West and mixed-terminating South Holgate Glacier – East shared a joint terminus through 2005 and separated into two distinct termini by spring of 2006. While the glaciers shared a terminus, they were mapped as two distinct features with a shared edge located approximately where the two glaciers merged.

Northeastern Glacier (−2.07 km, −2.43 km^2) experienced periods of both advance and retreat along its centerline between 1984 and 2021, particularly due to observed seasonal variations in size. However, its overall trend has been of retreat and lower glacier and terminus area loss, and the net length and area losses were substantial.

Sunlight Glacier (−0.61 km, −0.91 km^2) lost both substantial centerline length and lower glacier and terminus area between 1984 and 2021, at variable rates. In the early 2010s the glacier underwent a readvance of ∼300 m. Young alder growth on the debris-covered surface of the glacier also suggests a recent slowdown of glacier flow.

Paguna Glacier (+0.21 km, −0.03 km^2) was the only land-terminating glacier that substantially advanced along its centerline between 1984 and 2021. However, the rate of advance slowed each decade, and the terminus position was stationary from ∼2007 to 2021. The glacier's area fluctuated between growth and loss; the lower glacier area experienced insubstantial loss, while the terminus area experienced substantial gain. Lateral ice loss exceeded the area gained by terminus advance.

Dinglestadt Glacier (−0.90 km, −0.75 km^2) gained centerline length and lower glacier area between 1984 and 1991, but retreated and decreased in area from 1991 to 2021, resulting in an overall substantial net loss of both length and lower glacier and terminus areas.

Both arms of Split Glacier (−0.55 km, −0.68 km^2) experienced periods of both retreat and advance along its centerline, resulting in an overall substantial net loss of both length and lower glacier and terminus areas. While the majority of area lost was at the terminus, the north arm experienced more lateral ice loss than the south arm.

4.4. Mixed-terminating glaciers

Mixed-terminating glaciers were observed to be some combination of land-terminating, lake-terminating and/or tidewater over the course of our study period. There were four glaciers with mixed termination types: South Holgate Glacier – East, Reconstitution Glacier, Southwestern Glacier and Petrof Glacier. Most of these glaciers transitioned between termination types in the 2010s and experienced accelerated retreat from 2015 or 2016 through 2021. Petrof Glacier was the exception as it transitioned and accelerated earlier than the others. All of these were either relatively static in area and centerline length or advanced between 1984 and 1992, after which all followed a variable but overall decline in both lower glacier area and centerline length (Figs 5g, h). The majority of measured area loss in the lower glacier was at the terminus at South Holgate Glacier – East and Reconstitution Glacier, while at Southwestern and Petrof Glaciers the majority of area loss in the lower glacier was along the margins. Continuous seasonal measurements indicated that these mixed-terminating glaciers tended to retreat during the summer, with the exception of Reconstitution Glacier, which tended to advance. Summer length change tended to be greater than the typical image resolution, except at Petrof Glacier. Winter behavior was more variable, with South Holgate Glacier – East and Southwestern Glacier tending to advance, and Reconstitution and Petrof Glaciers tending to retreat. In the winter, only the retreat at Reconstitution Glacier and the advance at Southwestern Glacier were greater than the typical image resolution.

South Holgate Glacier – East (−1.26 km, −0.47 km^2) terminated in the tidal zone until 2014, after which observations indicated it has only terminated on land. Shortly after this, between 2015 and 2016, the glacier appeared to retreat rapidly along its centerline, then slowed and began to split into two fingers to retreat around a bedrock knob. This rapid retreat was the result of significant steepening of the underlying bedrock near the terminus. In 2016, the glacier thinned dramatically along this nearly vertical slope, eventually separating into an upper and lower terminus along the bedrock wall; we mapped the upper terminus that remained connected to the rest of the glacier. All centerline length and lower glacier and terminus area changes were substantial.

Reconstitution Glacier (−0.31 km, −0.42 km^2) was purely tidewater from the beginning of our study period until 1999, terminated in the tidal zone from 1999 through 2014, then became purely land-terminating through 2021. Like Ogive Glacier, Reconstitution Glacier's small size and debris cover made it difficult to map from satellite images. However, despite this uncertainty, Reconstitution Glacier experienced a strong trend of retreat and area loss; all centerline length and lower glacier and terminus area changes were substantial. Reconstitution Glacier's name comes from the fact that the glacier is separated from its accumulation zone and receives snow and ice primarily from icefall and avalanches.

Southwestern Glacier (−1.55 km, −1.38 km^2) was a predominantly land-terminating glacier until it began developing a proglacial lake in 2013, and it terminated in the lake from 2014 through 2016. After 2016, the terminus retreated beyond the lake, while the lake persisted and grew slightly larger. All centerline length and lower glacier and terminus area changes were substantial.

Petrof Glacier (−1.03 km, −2.33 km^2) was a lake-terminating glacier that retreated onto a bedrock knob and became land-terminating in 2006. The proglacial lake expanded slightly between 1984 and 2006 as the terminus retreated, although part of the area revealed by terminus retreat during that time was bedrock. All centerline length and lower glacier and terminus area changes were substantial.

5. Discussion

Of the 19 glaciers in this study, 13 substantially retreated along their centerlines, 14 substantially lost lower glacier area and 14 substantially lost terminus area between 1984 and 2021. Two glaciers both substantially advanced and gained terminus area, and none of the glaciers substantially gained lower glacier area. All four glaciers that did not experience a substantial centerline length change were tidewater glaciers; similarly, four of the five glaciers that did not experience a substantial lower glacier area change, and all three of the glaciers that did not experience a substantial terminus area change, were tidewater. This relative lack of ice loss at the tidewater glaciers is consistent with the findings of Larsen and others (2015) that Alaskan tidewater glaciers are losing mass at a much slower rate than other Alaskan glaciers. Although our dataset is limited in the availability of continuous seasonal measurements, our seasonal data indicate that most glaciers tended to retreat in the summer, while winter behavior was more variable (Table 3). For most glaciers, the median seasonal

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variability was less than the image resolution for at least one season. Overall, all tidewater glaciers tended to advance during winter and retreat during summer, all lake-terminating glaciers tended to retreat during both winter and summer and land-terminating and mixed-terminating glaciers tended to retreat during the summer and showed a wider variety of winter behaviors (Table 3). There were no glaciers with a tendency to advance during both winter and summer.

Mass-balance studies at other Alaskan maritime glaciers (e.g. Wolverine Glacier on the Kenai Peninsula and Lemon Creek, Taku and Mendenhall Glaciers on the Juneau Icefield in southeast Alaska) indicate that summer temperatures are driving negative mass balances through ablation processes, such as the areal retreat that we report on here (Motyka and others, 2003b; Criscitiello and others, 2010; O'Neel and others, 2019; McNeil and others, 2020). More specifically, studies at nearby Wolverine Glacier, ~60 km northeast of Bear Glacier (the most northern glacier in our study), indicate that sensitivity to summer conditions is a recent change and that previously, winter precipitation drove mass balance (Bitz and Battisti, 1999; Josberger and others, 2007; O'Neel and others, 2019). Wolverine and Lemon Creek Glaciers are US Geological Survey Benchmark Glaciers, with long-term records of mass-balance change. Both Wolverine and Lemon Creek Glaciers experienced cumulative mass loss over the period of record and saw an increase in the rate of mass loss since 1990, which is broadly consistent with our observations of ice area loss at many glaciers in Kenai Fjords National Park. If temperatures warm in either winter or summer or, worse, in both seasons, there will be an increase in the rate of mass loss at the park's maritime glaciers. Further, we speculate that the exposure of rock around these glaciers enhances the microclimate and summer melt, leading to increased ablation and greater mass loss. Given this study's glaciers' lower elevations and proximity to the ocean, we speculate that the mass loss of these glaciers may be higher than that observed at Wolverine and Lemon Creek Glaciers.

The glaciers in this study (except Bear Glacier) tend to be smaller with lower elevation ranges than Wolverine, Lemon Creek, Taku and Mendenhall Glaciers, and they terminate nearer to the ocean than all but Taku Glacier. McGrath and others (2017) determined that smaller glaciers and glaciers outflowing from icefields have a higher mass-balance sensitivity to projected climate change. Most of our study glaciers are located with their termini at low elevation (at or slightly above sea level). Although we have not measured mass balance, looked at temperature or precipitation within the fjords or conducted studies to look at annual equilibrium line of altitude variations, the average accumulation season (October–April) temperature in nearby Seward, Alaska hovers around freezing (32.11°F based on the 1991–2020 normal) (NOAA National Centers for Environmental Information, 2021). A slight increase in winter temperatures over the nearby glaciers would result in precipitation changing from snow to rain, impacting seasonal snow accumulation, and would increase the likelihood and amount of melt over the winter.

5.1. Tidewater glaciers

All six tidewater glaciers in our study experienced periods of both advance and retreat along their centerlines between 1984 and 2021. These tidewater glaciers also tended to advance in the winter and retreat in the summer; in particular, Aialik Glacier and Holgate Glacier (in winter) and McCarty Glacier (in summer and winter) had median seasonal variations greater than the typical image resolution. Several of these glaciers did not experience substantial centerline length, lower glacier area and/or terminus area changes over the study period; only Northwestern Glacier experienced substantial changes in all three of these categories. Formerly-tidewater South Holgate Glacier – East and Reconstitution Glacier also experienced substantial centerline retreat and area loss, enough so that they both retreated onto land in 2014.

Table 4. Comparison of tidewater glacier length changes observed by McNabb and others (2015) from 1985 to 2013 with our observations from 1985 to 2021, split into measurements from 1985 to 2013 and 2013 to 2021

Name	1985–2013 ΔL (km)[a]	1985–2013 ΔL (km)	2013–2021 ΔL (km)
Aialik Glacier	0.17	0.03	0.00
Holgate Glacier	−0.46	0.05	0.47
McCarty Glacier	−0.84	−0.47	−0.19
Northwestern Glacier	0.23	−1.51	0.00

[a]Data from McNabb and others (2015).

McNabb and Hock (2014) found that between 1991 and 2000, 60% of Alaskan tidewater glaciers retreated, and between 2001 and 2010, 46% of those glaciers retreated; for our subset of glaciers, these percentages are higher, with 100% of the tidewater glaciers retreating between 1991 and 2000 and 66% retreating between 2001 and 2010. McNabb and others (2015) studied four of our six fully tidewater glaciers (Aialik, Holgate, McCarty and Northwestern Glaciers) from 1985 through 2013, and found length changes ranging from −0.84 km (McCarty Glacier) to +0.23 km (Northwestern Glacier). Splitting our study period into 1985–2013 and 2013–2021 for comparison (Table 4), we found that McCarty and Northwestern glaciers retreated, while Aialik and Holgate glaciers marginally advanced. Between 2013 and 2021, we found that McCarty Glacier continued to retreat and Holgate Glacier further advanced, while the lengths of Aialik and Northwestern glaciers did not experience net change. We attribute the differences between our data and those of McNabb and others (2015) to differences in methodology: McNabb and others (2015) used the box method to measure area and divided by width to estimate average length change, and averaged multiple seasonal observations to estimate annual lengths; we used the centerline method to directly measure length, and directly compared individual observations of length. We have also observed that at most of these glaciers, length change was not consistent across the width of the terminus, so the centerline length measurement will yield different results than length measurements made at other parts of the terminus. We cannot reconcile the large discrepancy between the measurements at Northwestern Glacier; however, based on retreat visible in satellite imagery we are confident in our observations.

Tidewater glaciers make up 14% of Alaska's total glacierized area, but between 1994 and 2013 they were only responsible for 6% of regional mass loss (Larsen and others, 2015). Tidewater glaciers are unique from other glacier types in that local geographic factors such as sedimentation (Brinkerhoff and others, 2017), fjord geometry (Mercer, 1961; Catania and others, 2018), water depth (Meier and others, 1980; Post, 1980a, 1980b), glacier geometry (Pfeffer, 2007) and ice speed and calving rates (Meier and Post, 1987; O'Neel and others, 2003; Ritchie and others, 2008; Post and others, 2011) can override the influence of climate change and can cause advance despite a negative mass balance (Larsen and others, 2015). These additional factors cause the advance and retreat of tidewater glaciers to be less dependent on climate change compared to the behavior of lake- and land-terminating glaciers (Trabant and others, 1991). This can result in asynchronous behavior relative to other local glaciers, even other nearby tidewater glaciers (Mann, 1986; Larsen and others, 2016). Larsen and others (2007) looked at volume changes in

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glaciers in southeast Alaska and Canada from 1948 to 1987 and found that several tidewater glaciers that had historically been retreating were in the advancing stage of the tidewater glacier cycle, as indicated by their expansion. In our study this asynchronicity is apparent at Holgate Glacier, which is the only tidewater glacier in Kenai Fjords National Park that was advancing as recently as 2021, and has oscillated between advancing and retreating during our period of record. Holgate Glacier's variable behavior is indicative of the classic tidewater glacier cycle (Meier and Post, 1987; Trabant and others, 1991), although Holgate Glacier's cyclical behavior occurs on a much faster timescale than classically described. Holgate Glacier's advance is likely due to the development of a shoal that was first observed and recognized as such in the field in 2020. High sedimentation rates allow tidewater glaciers to develop a submarine terminal moraine shoal that extends across the width of the fjord (Trabant and others, 1991). Although current elevation data are unavailable for this study, we speculate that Holgate Glacier's advance is associated with vertical thinning (Larsen and others, 2015) and there has not been an increase in ice volume, just terminal expansion due to shoal development. This shoal acts as a barrier to relatively warm marine waters that influence glacier melt and calving, thus allowing the glacier to advance while moving the moraine shoal forward. Because the development of a shoal can temporarily override the effects of climate change and allow a glacier to advance, once a glacier retreats back from the shoal it often experiences a rapid retreat such as that observed at McCarty and Northwestern Glaciers (Post, 1980a, 1980b), as well as at Columbia Glacier (Post, 1975).

Changes to tidewater glaciers will influence nearshore oceanography and marine ecosystems (Lydersen and others, 2014; O'Neel and others, 2015; Arimitsu and others, 2016). The local fjord marine environments are changing as changes in glacier melt result in changes to the volume of fresh water input (Neal and others, 2010), which affects local physical oceanographic properties such as temperature, salinity and turbidity (Etherington and others, 2007; Hood and Berner, 2009; Hood and others, 2009; Arimitsu and others, 2012, 2016; Jenckes and others, 2022), nutrients (Hood and Scott, 2008; Whitney and others, 2018) and currents (Royer, 1981). Meltwater and sediment discharge from tidewater glaciers drive fjord temperature and turbidity (Arimitsu and others, 2016). In cases where a tidewater glacier retreats onto land, for instance, water traveling from that glacier to the fjord will have a higher temperature and lower turbidity as it warms and drops sediment while traveling over land. These temperature and turbidity changes in turn affect nutrient concentrations and predator and prey abundances (Arimitsu and others, 2016); healthy predator–prey dynamics are important to ecotourism in the Kenai Fjords. Meltwater upwelling and iceberg calving from tidewater glaciers also help drive circulation patterns and the distribution of nutrients and planktonic food sources in fjords (Lydersen and others, 2014; O'Neel and others, 2015; Arimitsu and others, 2016; Urbanski and others, 2017), and tidewater glacier retreat from the marine environment could reduce or shut off the glacial contribution to fjord circulation. The ice-ocean interface also provides habitat for higher trophic-level species such as harbor seals who haul out on icebergs (Hoover-Miller and Armato, 2018; Womble and others, 2021) near Aialik, Northwestern and McCarty Glaciers and Kittlitz's murrelets that spend the summer breeding season near tidewater glaciers (Arimitsu and others, 2012).

5.2. Lake-terminating glaciers

All three lake-terminating glaciers in our study underwent substantial centerline retreat and lower glacier and terminus area losses between 1984 and 2021, as did Petrof Glacier, which was lake-terminating through 2006. These four glaciers experienced accelerated centerline retreat in the 2010s. In particular, during those years Bear Glacier and Pedersen Glacier experienced greater net retreats than tidewater Northwestern Glacier's retreat in the 1990s, which was both the longest and fastest tidewater glacier retreat that we observed. These large retreats are consistent with observations of lake-terminating Ellsworth and Excelsior glaciers in nearby Sargent Icefield, which have also retreated rapidly after exposing over-deepened beds (Molnia, 2007; Maraldo, 2020). These rapid retreats could result in increased ice loss from higher elevations as occurred at Yakutat Glacier. Located on the outer coast of southern Alaska between southcentral and southeastern Alaska, Yakutat Glacier experienced lake calving and subsequent terminus retreat that led to a drawdown of glacier ice and rapid thinning (Trüssel and others, 2013, 2015). In southeast Alaska, lake-terminating glaciers have similarly been observed to have greater volume losses than tidewater glaciers (Larsen and others, 2007). The lake-terminating glaciers in our study also tended to retreat during both the summer and winter; Bear Glacier and Yalik Glacier had median retreats greater than image resolution in the summer, while Pedersen Glacier did so in the winter.

The rapid retreat of Bear Glacier that began in 2018 was initiated by a glacier lake outburst flood that occurred in August 2018 (Kurtz and Wolken, 2019). This outburst flood was unusual in that it breached the moraine separating the lake from the ocean, resulting in a sudden decrease in water levels, allowing marine water to temporarily enter the lake at high tides. The temporary 2018 breach demonstrated the protection that the moraine shoal provides to Bear Glacier and the vulnerability of terminus stability to infiltration of marine water into the proglacial lake (Motyka and others, 2003a). Ice thickness measurements on Bear Glacier identified areas of grounding below sea level at a minimum of 6.5 km above the current terminus position (Truffer, 2014), indicating the potential for an unstable and rapid retreat (Larsen and others, 2015) and a twofold expansion of the proglacial lake. This highlights the vulnerability of other shoal-protected glaciers in Alaska, such as Taku Glacier in southeast Alaska (McNeil and others, 2020).

The retreat of lake-terminating glaciers in Kenai Fjords National Park has resulted in the expansion of their proglacial lakes. As with tidewater glaciers, lake-terminating glaciers can decrease proglacial lake temperatures, increase turbidity and alter biogeochemistry, which can limit nutrients and decrease biological productivity (Slemmons and others, 2013). As glaciers retreat and their proglacial lakes expand, new fresh water habitat is created for species such as sockeye salmon, which favor aquatic systems with lakes connected directly to the ocean via rivers for spawning and rearing (Milner and Bailey, 1989; Pitman and others, 2020). Numerous studies have been conducted in the maritime southeast Alaska environment of Glacier Bay to understand fresh water ecology and glacier retreat (Milner, 1987; Milner and Bailey, 1989; Milner and others, 2007), but little has been done in Kenai Fjords National Park. Past fish surveys were conducted in the park following the Exxon Valdez oil spill (Milner, 1990; Milner and Oswood, 1990). Recreationally, the proglacial lake at Bear Glacier is one of the most popular sites in the coastal areas of the park. Visitors travel to the lake via boats and helicopters to kayak, paddleboard and camp on the shores of the iceberg-laden lake. Lake expansion provides more area to explore in personal watercraft.

5.3. Land-terminating glaciers

Nearly all of the six land-terminating glaciers in our study, as well as mixed- but predominantly land-terminating Southwestern

Glacier, experienced substantial centerline retreat and lower glacier and terminus area losses between 1984 and 2021. The exception was Paguna Glacier, which substantially advanced and gained area at the terminus, but did not experience substantial lower glacier area change. Seasonally, land-terminating glaciers tended to retreat in the summer and have more variable behavior in the winter; however, median seasonal advance or retreat often fell below the typical image resolution. The glaciers with seasonal behavior greater than typical image resolution include Northeastern Glacier (summer and winter retreat), Sunlight Glacier and Split Glacier (summer retreat, winter advance) and Dinglestadt Glacier (summer retreat).

Paguna Glacier has several attributes that make it unique from the other glaciers in this study. It is smaller, terminates higher above sea level (~70 m a.s.l.), is not known to have been tidewater or a tidewater tributary during the Little Ice Age and has a higher percentage of debris cover than most glaciers in this study. This debris was deposited in 1964 when a magnitude 9.2 earthquake generated landslides in the Kenai Mountains and deposited debris on 50% of Paguna Glacier (Post, 1967). It is likely that this thick debris cover insulated the ice surface (Östrem, 1959), overriding effects of climate change on the glacier's surface melt, which allowed the glacier to advance for several decades. Although we have not analyzed surface elevation change in this study, we speculate that the contribution of mass in the form of rock debris resulted in a glacier response not unlike that observed following continued positive mass balance in which the glacier ice redistributes to a point of equilibrium. In this case, the debris not only insulated the glacier's surface, but the increase in mass resulted in an expansion of the glacier length. Through time, ice flow transported the debris to the ablation zone, further reducing climate-induced melt as the area most likely to melt was insulated. Based on field observations, the glacier now appears to be melting in place, and farther up-glacier the rates of mass loss are likely higher than near the debris-covered terminus (Rounce and others, 2021).

Nearby Sunlight Glacier, which also received debris from the earthquake, did not advance. We suspect that this is because the landslide debris covered a smaller percentage of the entire glacier than on Paguna Glacier and because a higher percentage of the glacier is at a lower elevation than on Paguna (i.e. the Accumulation Area Ratio was lower than Paguna Glacier's at the time of the earthquake). Therefore, the percent of area of debris insulation and the input of mass were smaller than on Paguna Glacier.

The retreat of land-terminating glaciers in Kenai Fjords National Park has been accompanied by other terrestrial changes, including the development of forests and river systems resulting in expanded habitat for coastal wildlife. For instance, as river systems and lakes develop in the wake of glacier retreat, this increases the availability of habitat suitable for salmon (Milner and Bailey, 1989; Pitman and others, 2020) and the wildlife that thrive on it such as black and brown bears and bald eagles. These terrestrial changes contribute to changes in the nearshore marine environment as nutrient and sediment availability and transport evolve with the development of the terrestrial landscape (O'Neel and others, 2015). The deltas observed at the Dinglestadt and Split stream outlets are examples of post-glacier retreat coastal habitat. Recreationalists can also be found on the lands that have been recently deglaciated by land-terminating glaciers. These forelands offer the flattest terrain in the park for exploring on foot and the rivers that lead from glaciers such as Southwestern, Sunlight and Northeastern Glacier provide a path to follow through the alder thickets. As Kenai Fjords' glaciers retreat, new recreational opportunities open up.

6. Conclusions

We have produced a multidecadal record of biannual observations of lower glacier outlines for 19 glaciers in Kenai Fjords National Park. Between 1984 and 2021, these glaciers cumulatively lost ~42 km^2 of ice area in their lower reaches (24 km^2 at their termini and 18 km^2 at their margins). Most glaciers lost substantial length and area, while only two gained substantial length and area. Most of the glaciers that did not experience substantial length, lower glacier area or terminus area changes were tidewater glaciers. In contrast, all lake-terminating glaciers and nearly all land-terminating glaciers experienced substantial centerline retreat and ice area loss. Seasonally, all tidewater glaciers tended to retreat in the summer and advance in the winter, while all lake-terminating glaciers tended to retreat in both the summer and winter; land-terminating glaciers tended to retreat in summer but showed more variable winter behavior.

Local effects resulting from the loss of ice in our study area impact both terrestrial and marine environments and change the distribution of land cover types. The loss of ice area will equal the gain or expansion of water bodies and/or coastal vegetation types and will change the viewscape and recreational opportunities for visitors. The fresh water rivers and lakes originating from glacier meltwater will form new aquatic and terrestrial vegetation habitats with impacts to the nearshore marine environment. The direct loss of glaciers and the indirect changes to the local fauna will likely impact tourism, as many people come to the Kenai Fjords to see calving tidewater glaciers and the abundant marine wildlife that thrive in the current conditions (Lambert and others, 2010; Kutzner, 2019; Salim and others, 2021).

Glacier changes have made untold impacts to the Alutiiq/Sugpiaq people who have inhabited coastal environments of southcentral Alaska for millennia. Today, Chugach Alaska Corporation and the Alaska Native Claims Settlement Act village corporations of English Bay and Port Graham are the largest non-federal stakeholders in the park. Traditional hunting and gathering activities have been minimal in the park during the 40-year period of our study. However, ecotourism activities are common, including an inholding where Port Graham leases land to a wilderness lodge located in Aialik Bay near Pedersen Glacier. The retreat of this glacier may impact the visitor experience at this site.

Climate change predictions indicate that glaciers in southcentral Alaska will continue to lose mass at current or increased rates. Given this rapid rate of change, our final 2021 measurement may no longer represent the current condition of every glacier in the database by the time of this publication. In order for resource managers to make informed decisions, they must understand current conditions, including glacier dynamics and subsequent land cover and habitat changes. These changes can help identify the potential for new geohazards related to glaciers such as ice falls, landslide potential resulting from rapid retreat and slope debuttressing, or the development of new ice-dammed lakes that could cause glacier lake outburst floods. Our observations of ice margins revealed the development of new land cover types and habitats where, four decades ago, there was ice. Most obviously, the Kenai Fjords viewscape is changing dramatically as tidewater glaciers retreat onto land and land-terminating glaciers retreat into the alpine or out of sight around a bend. Therefore, we recommend that this database, and similar measurements elsewhere, be updated on a timescale that is manageable by resource managers and meaningful for decision-makers. Given the dynamic nature of the Kenai Fjords, this could arguably be annually. Our measurements indicate that most of the glaciers in Kenai Fjords National Park are shrinking rapidly, leading to measurable annual landscape change.

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Data and code availability. The glacier termini digitized in this study are available on the US National Park Service Integrated Resource Management Applications (IRMA) Portal (https://irma.nps.gov/DataStore/Reference/Profile/2293309) (Black and Kurtz, 2022). The scripts used for image downloads and data analysis are available at https://doi.org/10.5281/zenodo.6331265 (Black, 2022). We acquired Landsat images from Google Cloud Platform (https://console.cloud.google.com/storage/browser/gcp-public-data-landsat), and glacier centerlines from IRMA (https://irma.nps.gov/DataStore/Reference/Profile/2221653) (Arendt and Rich, 2013).

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