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Quo vadis, Alsek? Climate-driven glacier retreat may change the course of a major river outlet in southern Alaska

Michael G. Loso [a,*], Christopher F. Larsen [b], Brandon S. Tober [c], Michael Christoffersen [d], Mark Fahnestock [b], John W. Holt [c,d], Martin Truffer [b]

[a] Wrangell-St. Elias National Park and Preserve, National Park Service, Copper Center, AK 99573, USA
[b] Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775, USA
[c] Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA
[d] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA

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ABSTRACT

Climate change-induced glacier retreat can have substantial localized impacts that often go unnoticed in the sparsely populated regions where they occur. Here we predict that retreat of Grand Plateau Glacier, in southern Alaska, USA, will reroute the outlet of a major river with consequences for human activity in this remote region. The glacier terminus separates Alsek Lake and the present Alsek River outlet from Grand Plateau Lake. In response to thinning and retreat of that terminus, both lakes have more than doubled in size since 1958. Laser altimetry shows that terminus thinning continued at rates of up to 10 m/yr from 2017 to 2020. Radar soundings show that the bed of the thinning glacier terminus extends to >400 m below sea level, and that the two lakes will become conjoined within at most a few decades as the terminus further retreats. We predict that Alsek River will then abandon its present Dry Bay outlet channel in favor of the much steeper outlet of Grand Plateau Lake, 28 km to the southeast. Anadromous fish and associated predators in the lower Alsek will need to adapt to this change. Traditional and modern human activities centered on Dry Bay include commercial fishing, subsistence and sport hunting and fishing, and the finishing point for a world-renowned wilderness rafting expedition. Under present management guidelines, those activities cannot be relocated to the predicted future outlet, which sits within the federally designated wilderness of Glacier Bay National Park.

1. Introduction

Glacier retreat in Alaska and adjacent Canada is a major contributor to global sea-level rise (Zemp et al., 2019), reflecting widespread, gradual, and largely predictable mass loss driven by increasing surface melt (Larsen et al., 2015). Local impacts of glacier retreat are in general poorly documented for most of the region's 27,000+ glaciers (Kienholz et al., 2015), but comparatively rapid changes to some glaciers have caused notable and sometimes spectacular landscape-level changes. Recent examples from rapidly deglaciating terrain include the development of a new fjord (Pfeffer, 2013), a landslide-induced tsunami (Higman et al., 2018), a glacier detachment-induced debris flow (Jacquemart et al., 2020), a watershed reorganization (Shugar et al., 2017), growth of new proglacial lakes (Larsen et al., 2007), and numerous glacier lake outburst floods (Miller, 2020; e.g. Motyka and Truffer, 2007). Despite the scale, rapidity, and potentially destructive impacts of such events, many of these—even when studied and described by the scientific community—have gone largely unnoticed by the general public due to the remote, sparsely populated character of the region. Equally important, but in many cases less dramatic, are the ecosystem-level effects of glacier changes (e.g. Milner et al., 2017; O'Neel et al., 2015; Womble et al., 2009). Driven by a changing climate, changing glaciers are fundamentally altering the landscapes around them, in many cases with little attention from the public.

Government agencies ostensibly have a mandate to “manage” such changes, particularly in the region's many protected areas, but this is in practice quite difficult. The ultimate cause of glacier change—climate—is outside the control of any single land management agency. Mitigation and/or adaptation actions may be difficult to identify or justify when many events go unrecognized, visitors are uncommon, landscapes are massive and remote, and vulnerable infrastructure is mostly limited to the few human settlements. Even where rapid (and even disastrous) changes are anticipated, the large scale and unpredictable timing of such changes makes effective solutions difficult to identify and enact (Dai et al., 2020; Krakow and DeMarban, 2020). Despite these challenges, some changes can be anticipated to have

* Corresponding author at: Wrangell-St. Elias National Park and Preserve, PO Box 439, Copper Center, AK 99573, USA.
E-mail address: Michael_Loso@nps.gov (M.G. Loso).

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such significant human impacts that they warrant attention and advance planning. Here we describe the context for, and human consequences of, one such change now occurring on the remote southern coast of Alaska.

The Alsek River presently enters the Pacific Ocean just downstream of Alsek Lake, which is itself impounded by a rapidly thinning tongue of Grand Plateau Glacier (Fig. 1). The Alsek is a major glacial river that originates in the interior icefields of Canada's Yukon Territory before breaching the coastal mountains of British Columbia and the US state of Alaska en route to the Pacific Ocean (2011-2020 statistics near outlet: daily mean discharge 1458 m^3/s, peak discharge 9288 m^3/s, U.S. Geological Survey Water Resources, n.d.). This river enters the Pacific in Dry Bay, a broad delta that has a long history of human occupancy and usage associated with fishing and hunting, and as an access corridor. The English name “Alsek” is derived from the Tlingit language word Aalseix', and the river corridor was a “highway” to the interior for the indigenous people living around Dry Bay as early as the 15th century (Beattie et al., 2000; De Laguna, 1972). The Alsek River flows through conservation lands on both sides of the international border that comprise North America's largest contiguous protected area, a UNESCO World Heritage Site (IUCN World Heritage Outlook, 2020), before entering Alsek Lake and finally passing through Dry Bay to the ocean. We present evidence to suggest that continued thinning of the Grand Plateau Glacier will soon connect Alsek Lake with informally named Grand Plateau Lake. This will allow the existing Grand Plateau Lake outlet to capture some or all of the Alsek's flow, potentially leading to a permanent avulsion (abandonment of an established river channel in favor of a new permanent course) in which the Alsek River abandons the Dry Bay delta with a cascade of consequences for human use there. Importantly, such a change would move the Alsek outlet from adjoining Glacier Bay National Preserve into designated wilderness of Glacier Bay National Park. This legislatively mandated distinction in land status presents a considerable obstacle to any effort to adapt existing human uses to this climate-driven, landscape-scale change.

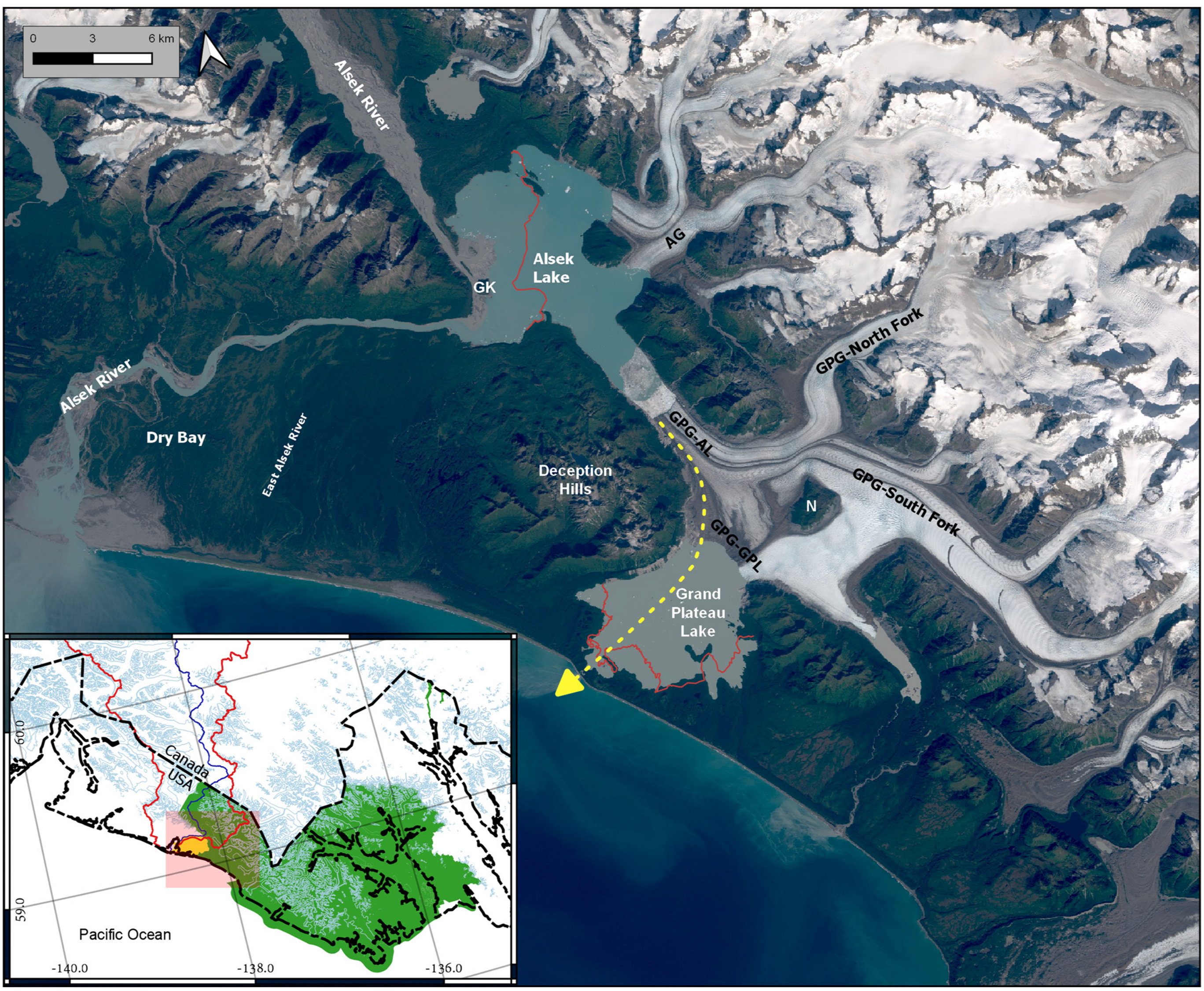

Fig. 1. Overview of the lower Alsek River/Grand Plateau Glacier study area. On main map, yellow dashed line is possible new outlet of Alsek River. GPG is Grand Plateau Glacier; -AL and -GPL are its Alsek and Grand Plateau distributary lobes, respectively. AG is Alsek Glacier, GK is Gateway Knob, and N is an unnamed nunatak. Red lines show extent of Alsek and Grand Plateau lobes in 1958; both lake basins were completely occupied by glacier ice in 1928 International Boundary Commission map. Inset shows location of the main map (red rectangle) in southern Alaska and adjacent Canada. Blue line is Alsek River, red line is Alsek watershed boundary, and light blue polygons are glacier cover from RGI 6.0. Green polygon is Glacier Bay National Park, and the yellow polygon is Glacier Bay National Preserve, centered over the lower Alsek River and Dry Bay. Base is Sentinel-2 image acquired September 10, 2018; Albers equal area projection.

2. Methods

2.1. Glacier extents and surface elevations

Terminus positions for the Alsek and Grand Plateau lobes of Grand Plateau Glacier were digitized from the best-available (primarily minimal cloud cover; secondarily highest sun angle) true-color Landsat image from each year's melt season between 1981 and 2019. Satellites used include Landsat 2, 3, 4, and 5 (60 m spatial resolution), and Landsat 7 and 8 (30 m resolution). Image information is presented in Supplementary Appendix, Table 1. Manual digitizing was conducted at a 1:25,000 scale and was completed only for the distinct boundaries where these glacier lobes terminate in proglacial lakes. We estimate the planimetric digitizing error as +/− 1 pixel (30 or 60 m, depending on satellite). Glacier surface elevations were collected through NASA's Operation IceBridge (OIB) by aircraft-based laser altimetry systems described, with detailed methodology, by Johnson et al. (2013). Average annual thinning rates shown in Fig. 2 were calculated by first calculating the average surface elevation from all laser returns within each 2.5 m pixel, then differencing the mean elevations in all pixels with data from both 2017 and 2020 campaigns. Mean elevation changes were then divided by the elapsed time in decimal years (2017 day 136 to 2020 day 157; 3.06 years) to yield annual rates. Glacier surface elevation profiles shown in Fig. 3 were extracted from laser altimetry data by averaging all returns within 100 m (along transect) by 100 m (buffer to 50 m to either side of transect) pixels. These elevations and lake surface elevations derived from laser altimetry are orthometric heights above NAVD 88, converted from GNSS using the GEOID12B geoid model. Transect locations were selected to maximize overlap among the coverages at multiple epochs. For epochs 2011, 2014, 2017, and 2020, data coverage was uniform across the full width of the 100 m wide buffered transect. For epochs 2005 and 2009, however, data are limited to a single track within the transect and may, where the glacier surface has significant across-transect topographic variability, bias the average elevation in comparison with broader coverage in subsequent epochs. This bias is most pronounced where the transects cross medial moraines or diverge significantly from the along-flow trajectory of the glacier.

2.2. Glacier bed elevations

Interpretation of airborne radar sounding profiles acquired by OIB provides measurements of glacier bed elevation. The four radar profiles analyzed herein were collected on June 5th, 2020 by the Arizona Radio Echo Sounder (ARES), operating at a 2.5 MHz center frequency with 2.5 MHz of bandwidth (Holt et al., 2019). Glacier bed locations were

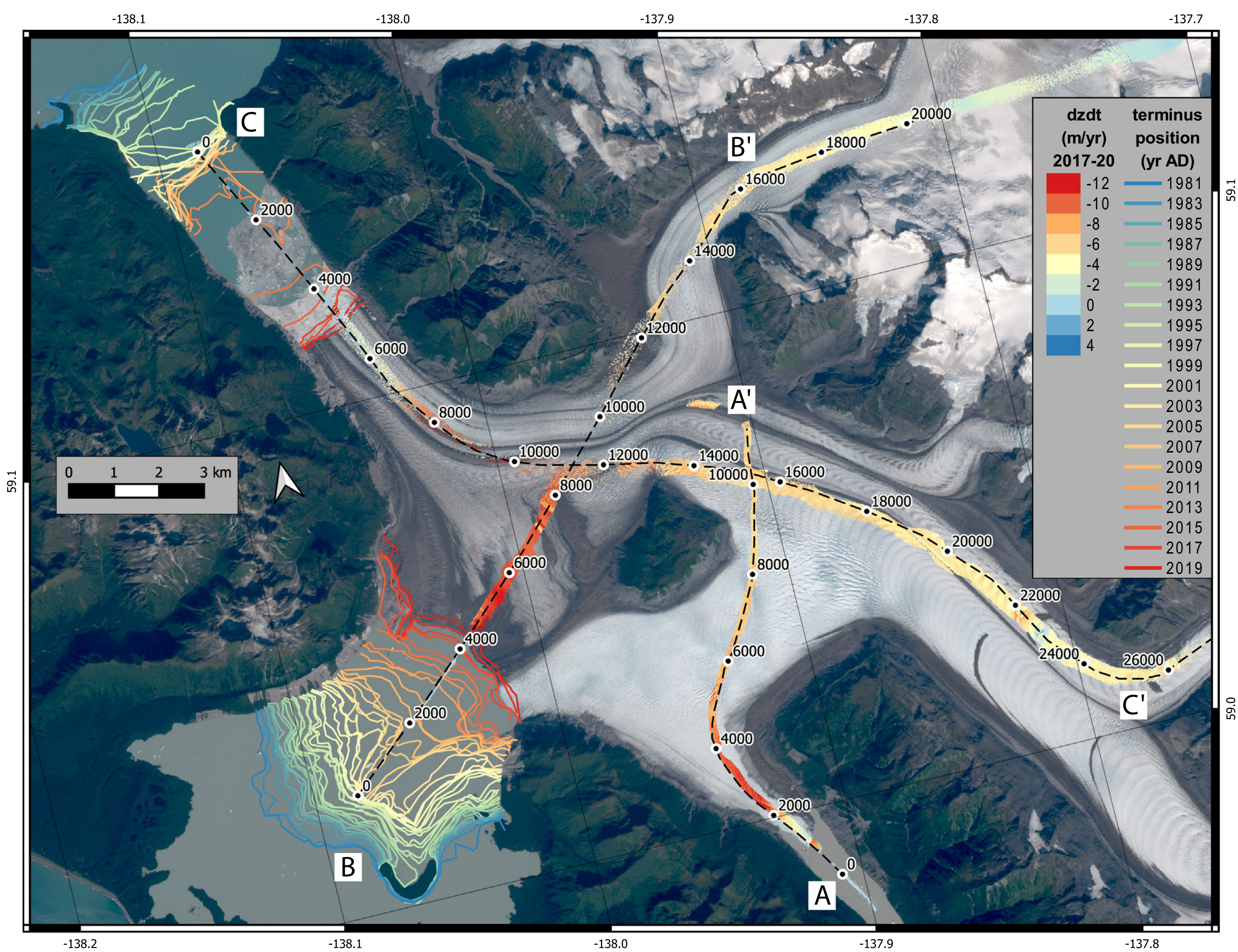

Fig. 2. Recent evolution of Grand Plateau Glacier. Annual terminus positions from 1981 to 2019 are shown for both Grand Plateau and Alsek lobes (legend omits even years for brevity). Average annual surface elevation change rates (m/yr) are derived from laser altimetry data collected in 2017 and 2020. Dashed black lines show transect locations and longitudinal distances from origin (m) for glacier surface profiles shown in Fig. 3. Base is Sentinel-2 image acquired September 10, 2018; Albers equal area projection.

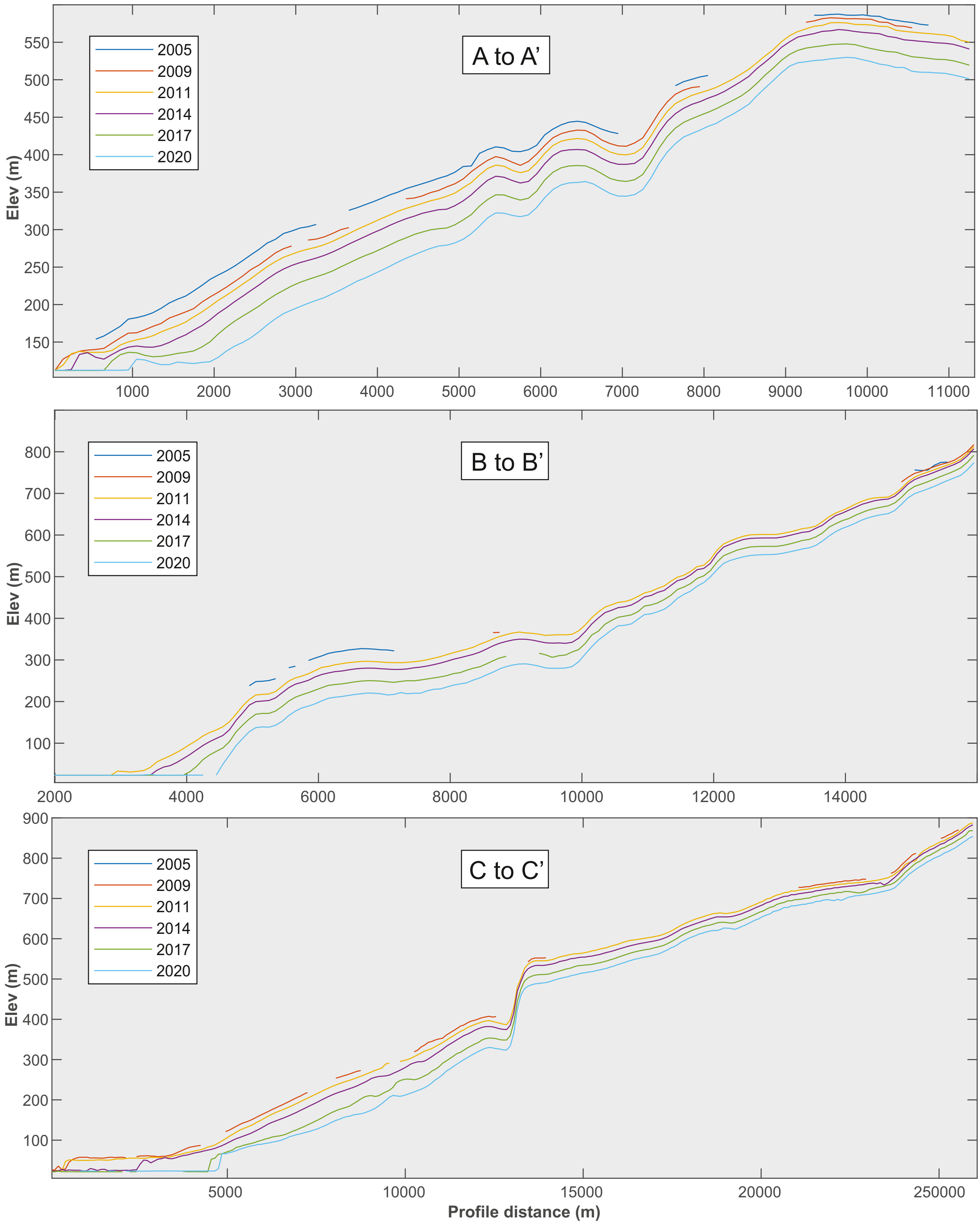

Fig. 3. Glacier surface elevation profiles extracted from three transects mapped in Fig. 2. Elevations based upon laser altimetry data averaged in 100 m pixels centered along the transect. Gaps are areas where the transect intersects no data for a given year. Elevations are heights above NAVD 88 derived from 2020 data.

digitized in radar profiles using the Radar Analysis Graphical Utility (Tober and Christoffersen, 2020). To ensure that the reflector being interpreted as the bed of the glacier is not a return from off-nadir surface topography, or "clutter," radar profiles were compared to simulated surface clutter profiles prior to interpretation and digitization (Holt et al., 2006). Contemporaneous laser altimetry measurements of surface elevation are utilized to calculate a two-way travel time delay through the glacier and to the bed, as the glacier surface is not visible in the radar profiles due to the combination of radar pulse duration and the altitude required for laser altimetry operations. Englacial two-way travel time delays are converted to ice thickness by assuming a relative dielectric permittivity of 3.15 (Evans, 1965). The calculated ice thickness is then subtracted from the surface elevation measured by laser altimetry to obtain bed elevations. Crossover analysis of OIB radar sounding data acquired over Malaspina Glacier demonstrates a bed elevation accuracy of 17.49 ± 13.64 m (Holt et al., 2019; Tober et al., submitted). This uncertainty is <10% of typical ice thicknesses measured in the present study. Glacier bed elevations are heights above NAVD 88 converted from GNSS using the GEOID12B geoid model. Where we lack radar soundings at the two glacier lobe termini, we inferred the trend of distal deepening by estimating the minimum water depth necessary to support the floating glacier tongues visible in each lake in the 2011 laser altimetry. For each lobe we first estimated the freeboard (f) of the floating tongue by subtracting the measured lake elevation from the surface elevation of the quasi-horizontal (and presumed floating) glacier tongue. We then calculated minimum flotation water depth (d) as $d = (f * \rho_i)/(\rho_w - \rho_i)$ where ρ_i and ρ_w are densities of glacier ice and water, respectively.

2.3. Ice velocities

Ice flow fields are NASA MEaSUREs ITS_LIVE annual velocity composites (Gardner et al., 2018), which are annual means of all available Landsat image pair velocities derived with autoRIFT feature tracking (Gardner et al., 2020). Ice flow vectors have been reprojected to UTM zone 8 N from the polar stereographic projection of the original velocity composites.

2.4. River profiles

River profiles and stream gradients are based upon the Alaska IfSAR product (Archuleta et al., 2017), an elevation dataset collected using interferometric synthetic aperture radar and posted with 5 m spacing. Elevations are heights above NAVD 88. Nominal vertical accuracy is 3 m and horizontal accuracy is 12.2 m CE90 (Archuleta et al., 2017). Data downloaded from the National Map Viewer were collected between August 14 and September 8, 2012. Elevations were extracted from pixels intersecting hand-digitized lines that follow the approximate thalweg of the extant rivers, and that follow the most direct path from inlet to outlet when crossing portions of lakes. Bumps in the extracted profiles, interpreted as elevation artifacts, icebergs, or mid-channel bars, were manually removed from all profiles.

3. Results

3.1. Glacier extents and surface elevations

By the early 1900s, the conjoined ice masses of Alsek Glacier and Grand Plateau Glacier completely filled the basins we now refer to as Alsek Lake and Grand Plateau Lake, forcing the Alsek River to pass through a narrow corridor between Gateway Knob and the Deception Hills (Fig. 1) before entering Dry Bay (International Boundary Commission, 1928). Since that time, both lakes have grown at the expense of the retreating termini of those glaciers (Larsen et al., 2007). Topographic maps indicate that by 1958 the two lakes were approximately half their present sizes (U.S. Geological Survey, 1959) and we will show that their growth is now accelerating. Alsek Glacier separated from the Alsek lobe of Grand Plateau Glacier around 1995, and since then the two lakes have been separated only by the bifurcated terminus of Grand Plateau Glacier.

Here, we first present the recent history of Grand Plateau Glacier retreat that has allowed continued growth of those lakes, documenting changes in mapped glacier margins and deflated glacier surface elevations. Second, we present a time-series of rapidly evolving ice surface velocities showing dynamic adjustments to the changing glacier geometries. Third, we use ice-penetrating radar to show that the glacier bed is deep enough to allow a direct subaerial connection between the two lakes once the terminal lobes are sufficiently retreated. Finally, we examine the geomorphology and longitudinal profiles of the existing Dry Bay outlet and possible Grand Plateau outlet to consider the likelihood of river course rerouting once the lakes are connected.

Between 1981 and 2019, lake terminating margins of Grand Plateau Glacier have retreated substantially (>7 km retreat for the Alsek lobe and >5 km retreat for the wider Grand Plateau lobe) from their respective basins (Fig. 2). Terminus retreat rates were highest on the Alsek lobe during the period 2011-2016, including rapid terminus retreat of over 3 km during the summers of 2014 and 2015. The 2014-2015 retreat pulse filled Alsek Lake with enough calved icebergs to block downstream passage of Alsek River recreational rafters through late summer 2016. Between 1981 and 2019, glacier retreat caused Alsek Lake to nearly double in area from 79 km^2 to 137 km^2. Retreat rates were steadier on the Grand Plateau lobe during this period, with only a slight acceleration between 2007 and 2011 and no dramatic changes coincident with the 2014-2015 event on the Alsek lobe. Grand Plateau Lake, also nonexistent in the early 20th century, grew from 43 km^2 to 92 km^2 between 1981 and 2019.

Grand Plateau Glacier terminus retreat was accompanied by significant surface lowering over the last half of the 20th century (Larsen et al., 2007), and surface elevation profiles measured since 2005 reveal continued widespread lowering that accelerated after 2014 (Fig. 3). Averaged annual surface elevation changes over the most recent epoch (2017-2020) are shown in Fig. 2 and reach maximum rates exceeding −10 m/yr over surveyed portions of the lower Grand Plateau lobe. The average lowering rate is more modest over the lower Alsek Lobe, closer to −2 m/yr. Profile C-C′ in Fig. 3 reveals the likely explanation for this discrepancy in observed lowering rates. Over 3 km of the Alsek lobe terminus was flat-lying and likely floating in Alsek Lake in 2009. The sub-horizontal portion of that profile persisted with a calving terminus approximately 30 m high through 2017, indicating that at least some of the recent glacier thinning has been accommodated by the buoyant portion of the terminus. It appears that a portion of the Grand Plateau lobe (profile B-B′) was floating with 7-8 m of freeboard in 2011 (there are no data from 2009 or earlier), but thinning rates there have subsequently been quite high, suggesting that Grand Plateau lost its floating tongue sooner than the Alsek. The rapid recent thinning along B-B′ may have an additional explanation that we consider next.

3.2. Ice flux and glacier bed elevations

The glacier changes described above can be partly explained by the evolving pattern of ice flux from Grand Plateau's tributaries into the Alsek and Grand Plateau tributary lobes. We infer flux changes from the evolution of remotely sensed glacier surface velocity and medial moraine positions at four epochs between 1985 and 2018 (Fig. 4). The most obvious change during that interval is the significant acceleration of flow down the Alsek lobe sometime after 1995, which is evident in both the 2013 and 2018 datasets. This acceleration is related in part to shortening and retreat of the glacier's calving terminus, increasing overall slope. It also largely reflects gradual capture, by the Alsek lobe, of much of the flux from the South Fork Grand Plateau Glacier. In 1985, most of the ice from the South Fork was flowing into Grand Plateau Lake around both sides of a nunatak ("N" in Fig. 1). But between 1985 and 2018, ice flow along the north side of the nunatak into the Grand Plateau lobe terminus diminished almost entirely. Ice flux into that terminus continues to the present day along the south side of the nunatak, but medial moraines that split the South Fork Grand Plateau Glacier into three discrete trunks show that only a portion of the left-most trunk is contributing in 2018, compared with 1985 when the entirety of the South Fork was flowing into the Grand Plateau lobe terminus. The northern two trunks of South Fork flow were beginning to flow towards Alsek Lake by 2013, and in 2018 they were captured completely by the Alsek lobe, not only contributing additional ice flux but also forcing the

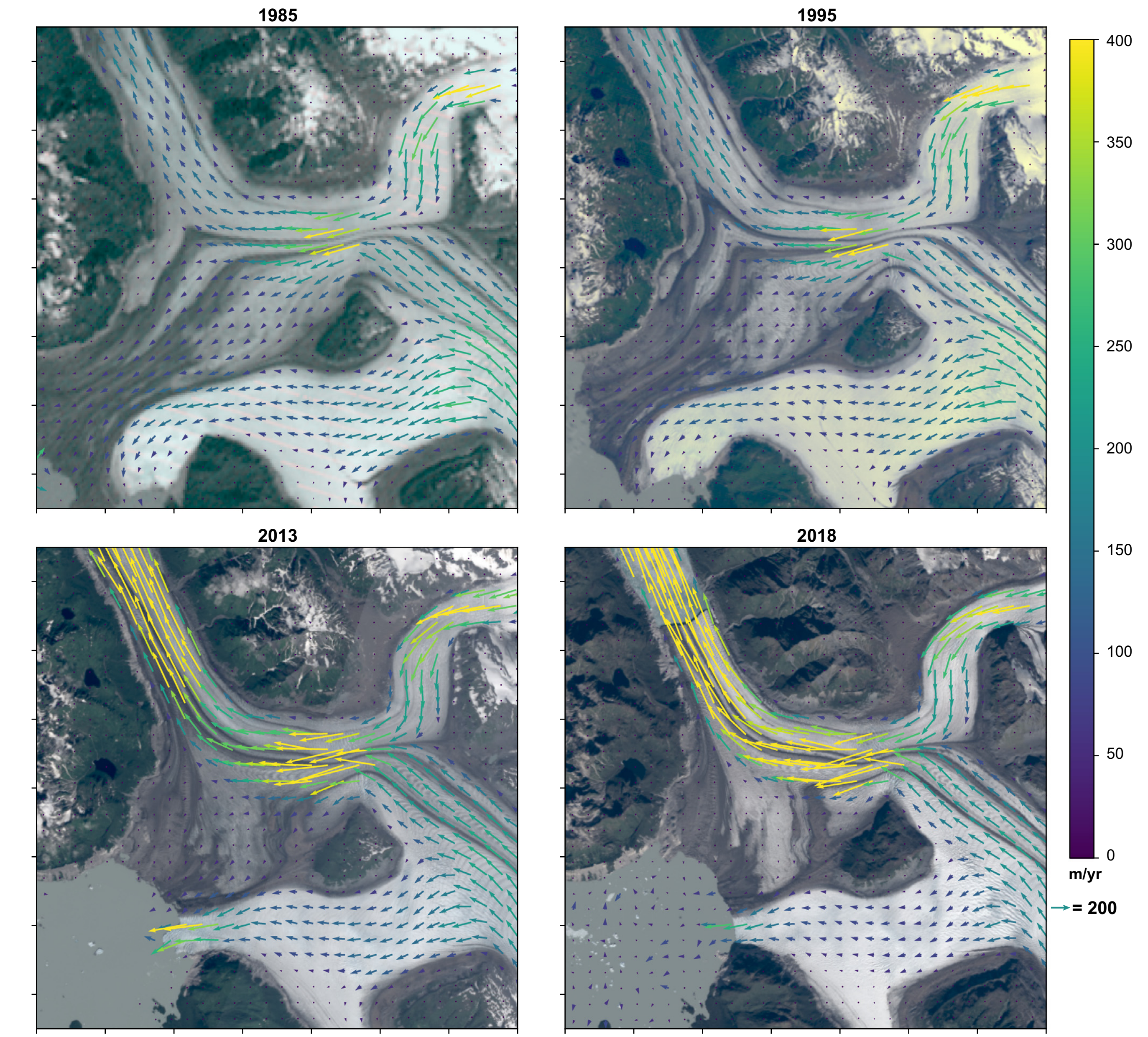

Fig. 4. Glacier velocities (meters per year) for the years 1985, 1995, 2013, and 2018. Velocity fields are plotted over Landsat images for the corresponding years (see SI Appendix, Table S1 for image dates), showing evolution of the ice margins and medial moraines over the same period. UTM zone 8 N projection.

North Fork flow into a comparatively narrower portion of the valley, both of which would potentially contribute to the higher velocities seen in 2013 and 2018. This reorganization of the ice flux means that the Grand Plateau lobe received significantly less ice from the Grand Plateau Glacier accumulation zone in 2018 than it had in the earlier epochs, including a virtual cessation of flow into the lake from the north side of the nunatak. The Alsek lobe had captured a higher fraction of the total flux by 2018, resulting in higher ice velocities despite the pattern of continued terminus retreat and thinning evident there over the same period.

The large amount of ice flux rerouting towards Alsek Lake suggests a much deeper channel that is able to funnel ice away from the Grand Plateau lobe. Indeed, glacier bed elevation data derived from radar soundings and checked against simulated radar surface clutter show a deep valley, extending to >400 m below sea level, towards Alsek Lake (Fig. 5, *Supplementary Appendix*, Figs. S1, S2). This depth will lead to buoyancy driven mechanical break up (calving), and virtually guarantee a continued retreat of that branch. Importantly, other surveyed portions of the Grand Plateau Glacier terminus between Alsek and Grand Plateau Lakes are also grounded significantly below sea level. Bed returns could not be definitively identified near the lake-calving front of Grand Plateau Glacier, but faster flow in the southern branch (Fig. 4) provides strong evidence that the bed there remains deep. It is therefore reasonable to expect continued retreat of the glacier will result in the formation of a single connected lake. As a matter of fact, laser altimetry data show consistently small differences in measured surface elevations between the two lakes (Alsek Lake level was 1.3 m higher than Grand Plateau Lake in 2014, 1.3 m lower in 2017, and 0.3 m higher in 2020 as shown in Fig. 5), which is a strong indicator that they are already hydraulically connected.

3.3. River profiles

Once the lakes do connect completely, Alsek River will have two potential outlets with distinctly different characters. The existing stretch of lower Alsek River from Alsek Lake through Dry Bay has a stream

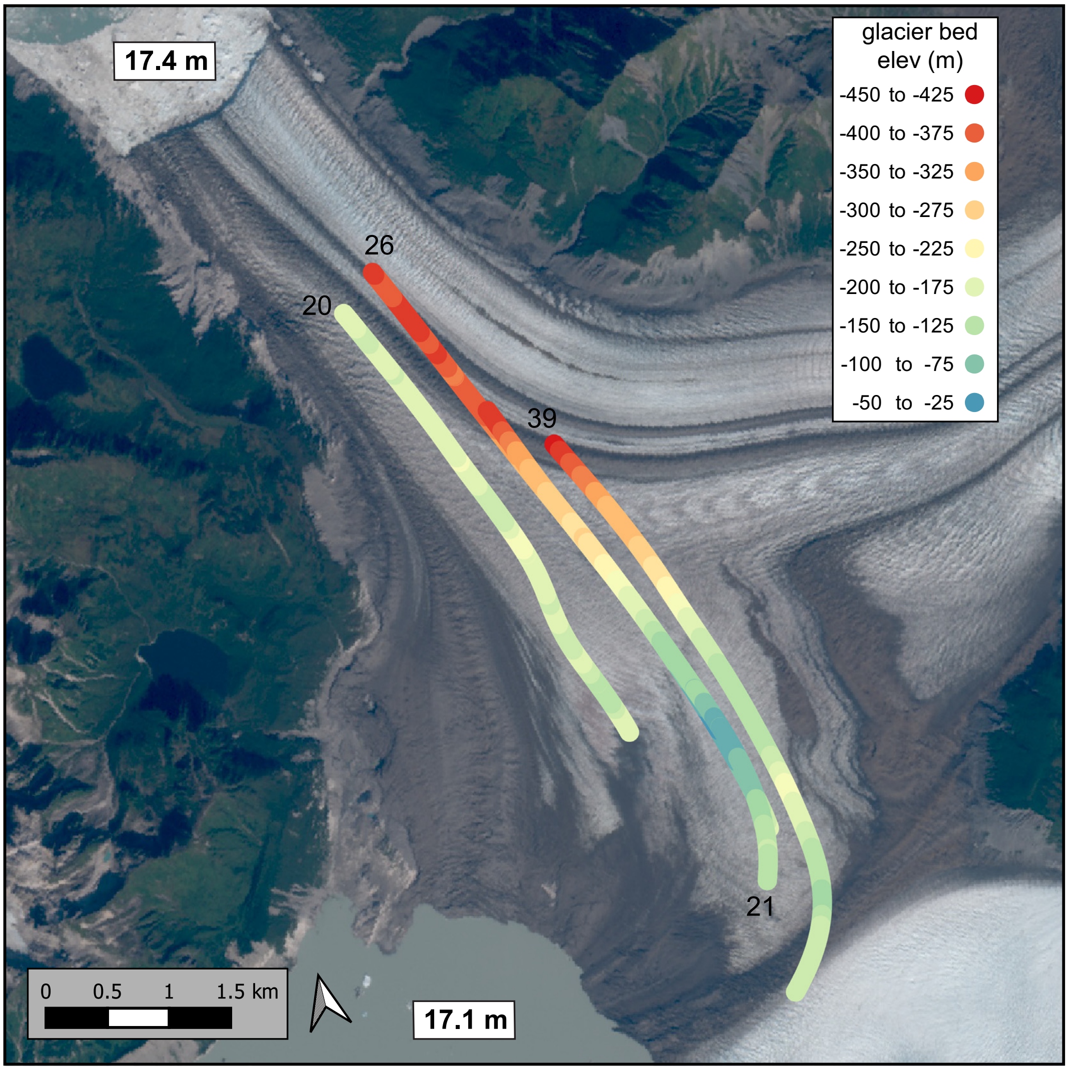

Fig. 5. Estimated glacier bed elevations along four ice-penetrating radar profiles on Grand Plateau Glacier. Underlying data, including comparison of overlapping profiles 21 and 26, are shown in the supplementary information; 2-digit codes identify individual profiles. Lake surface elevations shown over Alsek and Grand Plateau Lake are derived from 2020 laser altimetry data. Base is Sentinel-2 image acquired September 10, 2018; Albers equal area projection.

gradient of 1.3 m/km before flattening out in the tidal estuary, similar to the 1.8 m/km gradient of the upper Alsek River in its last 18 km upstream of Alsek Lake (Fig. 6a). The Grand Plateau Lake outlet is much shorter, with a gradient of 95.5 m/km between the lake and the beach. The steep, narrow (<50 m at its narrowest point) Grand Plateau outlet flow would have potentially greater erosive power, but flows in an unconfined channel over a boulder lag remnant of the glacier's Little Ice Age terminal moraine with the major axis length of many bed clasts exceeding 1 m (Fig. 6c). The existing Dry Bay outlet, in contrast, is a wide (>250 m at the narrowest point) and mobile braided stream with a bed dominated by sand and gravel (Fig. 6b).

4. Discussion

4.1. Imminence of Alsek River avulsion

Our results show clearly that Alsek Lake and Grand Plateau Lake are destined to join as one lake, based upon recent trajectories of change. Continued shrinkage of Grand Plateau Glacier is virtually certain and thinning in the terminus region that separates Grand Plateau and Alsek Lakes is accelerating (Figs. 2, 3). We do not attempt to quantitatively model the timing for complete deglaciation of the terminus region, but note that portions of the terminus in the stagnant zone near Grand Plateau Lake are generally 300-400 m thick and thinning at rates of up to 10 m/yr. These results suggest that even without enhanced surface ablation or calving—both of which are likely—there will be a subaerial connection between the two lakes in at most a few decades.

Radar soundings directly confirm that the glacier is bedded well below lake level throughout the surveyed portion of the terminus region. To infer bed depths in the most distal portions of the two lobes, where we lack radar profiles, we use surface elevations of the formerly buoyant tongues of both glacier lobes—measured by laser altimetry in 2011—to estimate minimum water depths necessary for flotation near the glacier termini at that time. Minimum water depths of 330 m at the Alsek lobe terminus and 80 m at the Grand Plateau lobe terminus support a conclusion that the beds of both lobes grow deeper between the surveyed radar profiles and the overdeepened lake basins into which they flow. Finally, the close coincidence of lake levels between the two lakes strongly suggests that a subglacial hydrologic connection has already been established, even if possibly intermittent and/or seasonal in nature.

Once the lakes are conjoined, will Alsek River abandon its existing outlet at Dry Bay in favor of the Grand Plateau outlet? Most studies of

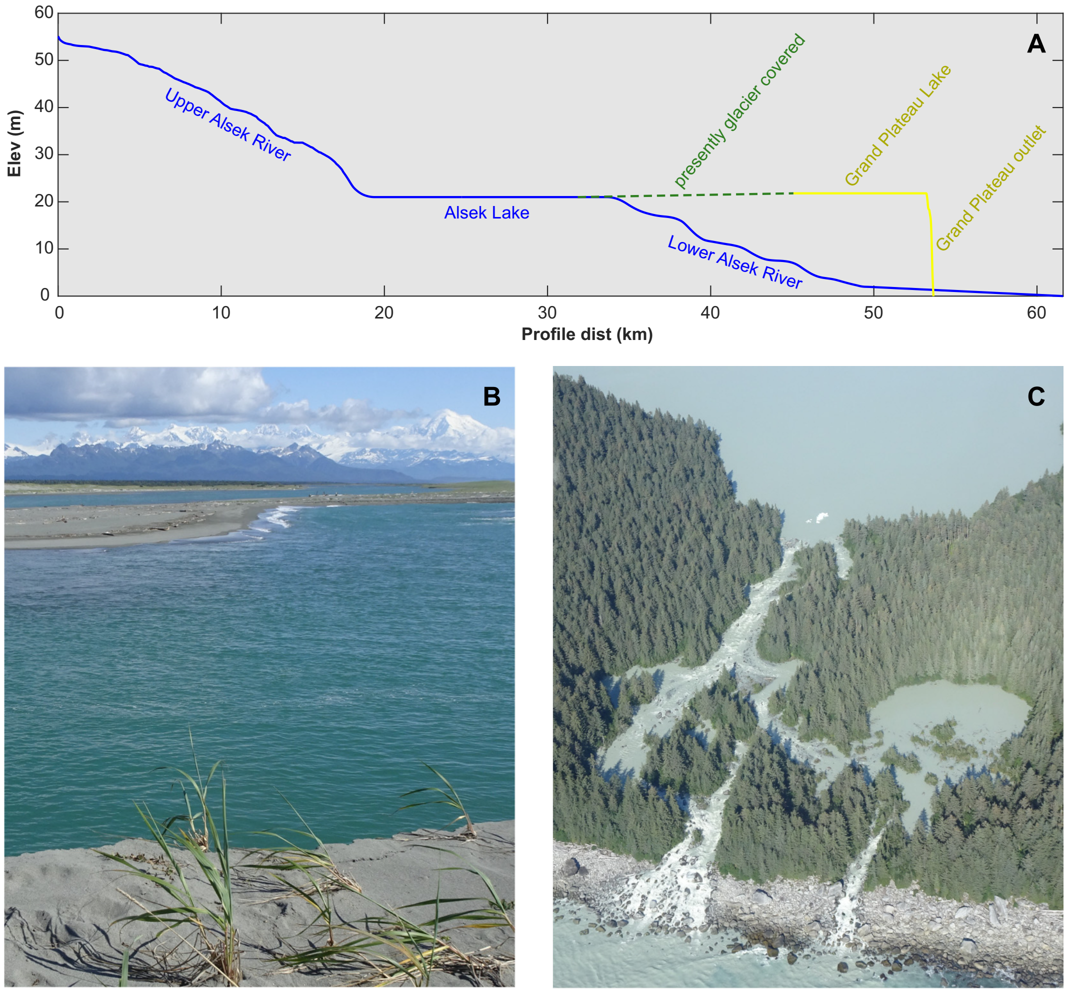

Fig. 6. Comparison of the present and possible future outlets of Alsek River. A) Longitudinal profiles of the current and possible future Alsek River from ~20 km above Alsek Lake down to the ocean. Blue line is smoothed profile of modern Alsek along a profile including shortest path across Alsek Lake. Yellow line is smoothed profile of Grand Plateau Lake and its modern outlet, connected to Alsek Lake by a dashed green line that represents the connected lake levels after glacier retreat. Elevations are IfSAR-derived heights above NAVD 88 (Archuleta et al., 2017). B) Ground level view of the lower Alsek River near tidewater. C) Aerial oblique view of the steep, boulder-armored Grand Plateau Lake outlet.

avulsion focus on autogenic processes in meandering alluvial rivers (Mackey and Bridge, 1995; e.g. Slingerland and Smith, 2004; Valenza et al., 2020), and are not strictly applicable to this situation in which the trigger is an allogenic forcing by glacier retreat. But in general, once a bifurcation exists in a channel system, the dominant channel will be determined by the relative balance of sediment erosion and deposition in the two channels, which in turn dictates the ability of the two channels to change their fluvial discharge capacities (Stouthamer and Berendsen, 2007). Because Alsek Lake functions as an efficient sediment trap for bedload and coarse suspended load from the upper Alsek River, sediment transport at the thresholds of both outlet channels is generally supply-limited. Both outlets are also impacted by ongoing post-Little Ice Age isostatic uplift of ~25 mm/yr (Larsen et al., 2005), augmented by periodic coseismic deformation. These factors suggest that the dominant channel will ultimately be the one most capable of increasing its discharge capacity through channel incision.

The slope of the extant Grand Plateau outlet is much steeper than the current lower Alsek outlet at Dry Bay (Fig. 6), providing it with comparatively higher stream power (73× greater) and unit stream power (364× greater per unit width) for an assumed equal potential discharge. We cannot say with certainty whether the enhanced sediment transport capacity engendered by this stream power advantage (Bagnold, 1966) would allow the Alsek River to more efficiently incise and ultimately adopt the Grand Plateau outlet, given the apparent resistance of its boulder-strewn bed to further sediment transport. But the boulders in that bed are a surficial lag derived from fluvial winnowing of finer sediments from the mixed grain size diamict of a Little Ice Age terminal moraine. Glacial rivers commonly cut through such moraines by selectively transporting the finer fractions, flowing around and under the largest, least mobile clasts. We also note that the Alsek River already has an established history of channel avulsion and abandonment in the Dry Bay delta. East Alsek River (Fig. 1) is one of two or three major channels that shared duty with the modern Alsek as major distributaries in the early 1900s (International Boundary Commission, 1928; Moser, 1902 pl. XLIII), but in response to isostatic and coseismic uplift those channels have been abandoned by mainstem Alsek flows over the course of the last century. We therefore consider it probable that the Alsek River will eventually abandon the final remaining channel in Dry Bay, re-organizing its flow to adopt the new Grand Plateau outlet in response to connection of the two lakes.

4.2. Consequences of Alsek River avulsion

We next consider impacts of the scenario we have described, in which climate-change induced retreat of the Grand Plateau Glacier allows the lower Alsek River to change course, abandoning its last 25+ km outlet through Dry Bay in favor of a shorter, steeper outlet to the east. The diminished Grand Plateau Glacier will calve into a much larger

Alsek Lake, and the lake level may drop slightly as river incision lowers the sill at the new outlet, but the most significant changes to the new landscape will occur in Dry Bay. Most obviously, there will no longer be a major glacial river draining through that portion of the landscape after abandonment, though there may be a period in which the channel is flooded occasionally by outflow from Alsek Lake during periods of high runoff. Similar to the East Alsek River, which was progressively abandoned earlier in the 20th century, Alsek River's abandoned channel will likely maintain a small perennial discharge fed by subsurface and groundwater flows and may therefore remain a suitable habitat for anadromous fish. But the East Alsek River's originally coarse fluvial gravels have largely been buried by fine sand and silt after becoming isolated from overbank floods, allowing encroachment of aquatic and riparian vegetation and over time diminishing the quality of East Alsek River as salmon spawning habitat (Clark et al., 2003; Faber, 2008). By analogy, we expect the abandoned lower Alsek River to become a sluggish, vegetation-choked clearwater stream surrounded by high brush and open forest. This process will degrade the abandoned Alsek River channel as salmon habitat, and possibly further diminish the East Alsek River by limiting shallow subsurface flows that recharge this and other remnant stream channels. Meanwhile any anadromous fish populations in the Alsek drainage will need to navigate the steep Grand Plateau outlet in order to maintain population viability. Numerous other ecosystem-level impacts of the glacier retreat and river course rerouting can be predicted (Milner et al., 2017; O'Neel et al., 2015), but we turn our attention next to the consequential impacts of these changes on human resource use.

Abrupt drainage reorganizations by large rivers can have major socioeconomic impacts on surrounding communities, and a long-feared capture of the Mississippi River by Atchafalaya Basin provides one well-known example of the tremendous efforts expended to understand and prevent them (McPhee, 1989). The causes and potential consequences of that avulsion obviously differ from the system considered here, but the fundamental problem is the same: human activities, institutions, and traditions have been built around the river's current location and are threatened if it moves. The Dry Bay area is not New Orleans, but in the context of the sparsely inhabited outer coast of southern Alaska, it has long been a hub of human activity. Alaska Natives lived in and traveled through the Dry Bay area for centuries since at least the end of the Little Ice Age (Beattie et al., 2000) because it had excellent fishing (including eulachon, dolly varden, and several salmon species), and because it occupied a strategic location on a coastal to interior travel corridor (De Laguna, 1972). Native occupation of the Dry Bay area flourished for centuries despite the challenges of such a dynamic glacial landscape, including a recurring history of catastrophic outburst floods (Clague and Rampton, 1982), but diminished over time as encroaching jurisdictional boundaries made traditional activities and travel too difficult (Cruikshank, 2001). These same factors—fishing and travel—have in a more commercial and modern context driven 20th century use of the Alsek River and its tributaries for commercial fishing, guided sport fishing and hunting, and recreational wilderness rafting.

The United States Congress has recognized and protected traditional subsistence uses, commercial fishing and hunting opportunities, and recreational human uses of the Dry Bay area, some of which are now threatened by the imminent rerouting of Alsek River (National Park Service, 2010). The 1980 Alaska National Interest Lands Conservation Act turned most of the recently expanded Glacier Bay National Monument into a National Park, but it purposefully treated the portion of the Monument in Dry Bay differently, creating a new 223 km^2 Glacier Bay National *Preserve* along the east side of Alsek River. The choice has been significant for subsequent management, which permits comparatively higher levels of human activity and associated developments. Within the Preserve are 8 airstrips, 3 NPS employee housing buildings, a public use cabin, 6 other NPS outbuildings, 110 km of maintained off-highway-vehicle accessible trails, a takeout facility and campground for approximately 800 wilderness rafters per year (about half of whom are commercially guided), commercial sockeye and coho salmon fisheries, a fish processor, 19 permanent fish camps (small cabins for commercial fishing operators), and 3 commercial hunting/fishing lodges. Additional facilities and fish camps are permitted on the US Forest Service-managed portion of Dry Bay west of the Alsek River. Most of the activities protected by the explicit intent of Congress and supported by these developments will become impossible or, at best, impractical if the Alsek River abandons the Dry Bay outlet. Critically, none of those developments will be permitted at the new outlet at Grand Plateau, which sits within the designated wilderness of Glacier Bay National *Park*.

5. Conclusions

Driven by climate-change induced glacier retreat, the lower course and mouth of the Alsek River appear poised to migrate into a protected area where most of the traditional, commercial, and legally protected activities in Dry Bay cannot legally follow. We have shown that accelerating glacier shrinkage will almost certainly connect Alsek Lake with Grand Plateau Lake within at most a few decades, and that subsequent avulsion of the lower Alsek River will likely follow. The landscape scale and ecosystem consequences of this change are substantial, even in the context of the rapidly evolving and largely glacier covered southern coast of Alaska. Even more unusual for this sparsely populated region is the range of expected socio-economic impacts. Traditional subsistence activities, commercial fishing, guided and unguided sport fishing, recreational rafting, and associated National Park Service infrastructure in Dry Bay are all dependent, to varying degrees, on the Alsek River. These impacts of the anticipated rerouting likely do not rise to a level that justifies engineered mitigation remedies of the scale or expense seen on more populated rivers like the Mississippi, and in any case will occur within lands managed by the National Park Service to protect natural processes. Like so many other consequences of global glacier retreat, this situation therefore clearly requires a multi-jurisdictional effort to consider, in advance of the potential future avulsion, the values of these ecosystem services and the adaptive management solutions that best preserve them (Milner et al., 2017).

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CRediT authorship contribution statement

Michael Loso: Conceptualization, Writing – Original Draft, Visualization, Formal analysis, Project administration **Chris Larsen**: Conceptualization, Writing – Review & editing, Investigation, Methodology, Funding acquisition **Brandon Tober**: Formal analysis, Data curation, Writing – Review & editing, Investigation, Visualization **Michael Christoffersen**: Formal analysis, Investigation, Software, Writing – Review & editing **Mark Fahnestock**: Formal analysis, Visualization, Data curation, Writing – Review & editing **John Holt**: Methodology, Funding acquisition, Resources, Supervision, Writing – Review & editing **Martin Truffer**: Conceptualization, Writing – Review & editing, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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