Mapping the rate of change of select glaciers using satellite and ground-based observations, Yukon and northwestern British Columbia

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Abstract

Glacier mass loss is accelerating throughout Yukon. This mass loss is confirmed by multiple studies and methods. New remotely-sensed and field-measured terminus retreat rates for select glaciers representative of the glaciated watersheds throughout Yukon are presented and compared to previous studies. Photographic data and measurements from field monitoring stations occupied from 2004 to 2022 confirm rapid mass-loss and provide relatable images for communicating the striking rate of glacier retreat. The rapid rate of glacier mass loss in Yukon will have variable impacts on downstream hydrology including discharge, temperature, chemistry, sedimentation and turbidity that are, with some exceptions, poorly quantified at present.

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Introduction

Glaciers are perennial bodies of ice that move under their own mass through internal deformation, deformation of their beds, and sliding. Glaciers grow when the input of snow and ice from precipitation exceeds the output of melt, evaporation, or calving at the terminus (Benn and Evans, 2014) and shrink when the reverse is true. Glaciers are dynamic systems and sensitive to changes in the earth's climate, primarily precipitation and air temperatures. In the north, air temperatures are warming at more than double the rate of the global average, driven by anthropogenic contributions of greenhouse gases into the atmosphere (Meredith et *al*., 2019). Global glacier mass loss has accelerated in tandem with atmospheric warming (Hugonnet et *al*., 2021). Glaciers have an important influence on various aspects of hydrological and ecological systems, including, but not limited to, fish habitat, water temperatures, flow regulation and hydropower generation. This study outlines the current state of glaciers in Yukon and northwestern BC, and how they have changed since the late 1980s. Eleven glaciers were selected from the upper Yukon River basin, six from the St. Elias Mountains, four from the Mackenzie Mountains, and three from the Coast Mountain Plateau (Fig. 1). This paper gives an overview of the history of Yukon's glaciations and recent glaciological studies, summarizes the findings from selected glaciers, and provides a foundation for future monitoring.

Glacial history

Glacial extent in Yukon has fluctuated considerably throughout the Quaternary, from massive ice sheets covering much of the territory, to large-scale recession during interglacial warm periods relegating ice to high alpine locations. The Pleistocene glaciations of Yukon were comprehensively mapped in 1999 (Duk-Rodkin). Duk-Rodkin (1999) identified three main glacial extents of the Cordilleran Ice Sheet (CIS), which was the main ice sheet in Yukon. These three main limits were: the pre-Reid, a composite of ten or more separate glaciations from the latest Pliocene to marine-oxygen isotope stage (MIS) 8 or 10 (Barendregt et *al*., 2010); Reid (MIS 6); and McConnell (MIS 2) glaciations (Fig. 1). Even during the least extensive of the three, the CIS covered a large portion of Yukon and British Columbia (Duk-Rodkin, 1999; Menounos et *al*., 2009). The CIS comprised several lobes flowing out from source regions in the St. Elias Mountains in southwestern Yukon, Ogilvie Mountains in the north, Selwyn Mountains in northeastern Yukon, Cassiar and Coast Mountains in northern British Columbia, and the Pelly Mountains in central Yukon. The McConnell Glaciation was the most recent and least extensive of the three glaciations, reached its maximum approximately 16 500 years ago, and disappeared by the beginning of the Holocene, approximately 11 700 years ago (Menounos et *al*. 2009).

Some of the larger present-day glaciers, such as those in the St. Elias and Coast Mountains, are remnants of the Pleistocene ice sheets, while many of the smaller glaciers would have disappeared completely and regenerated later in the Holocene (Calkin, 1988). The Neoglacial period, which includes the Little Ice Age (LIA), was a period of glacial advance following a warm interval of the early-mid Holocene (Menounos et *al*., 2009). Glacial advances in many areas of Yukon, northern BC and Alaska occurred around 3000 years ago, followed by some minor recession beginning about 2000 years ago (Calkin, 1988; Menounos et *al*., 2009). Some minor advance was seen about 1200 years ago, around the time when Mt. Churchill erupted, depositing White River ash in many areas of Yukon (Calkin, 1988). This was followed by reduced activity until the major advances of the LIA, between 434 and 84 years ago (Calkin, 1988). It is important to note that there is some spatial variation between episodes of glacial advance and recession throughout the Holocene, mainly controlled by climate and rates of precipitation in different areas of Yukon (Jackson et *al*., 1991). While LIA advances were relatively limited in extent, in some cases the effects of these advances extended much farther than the glacier termini through impoundment of drainages and subsequent catastrophic drainage (Clague and Rampton, 1982).

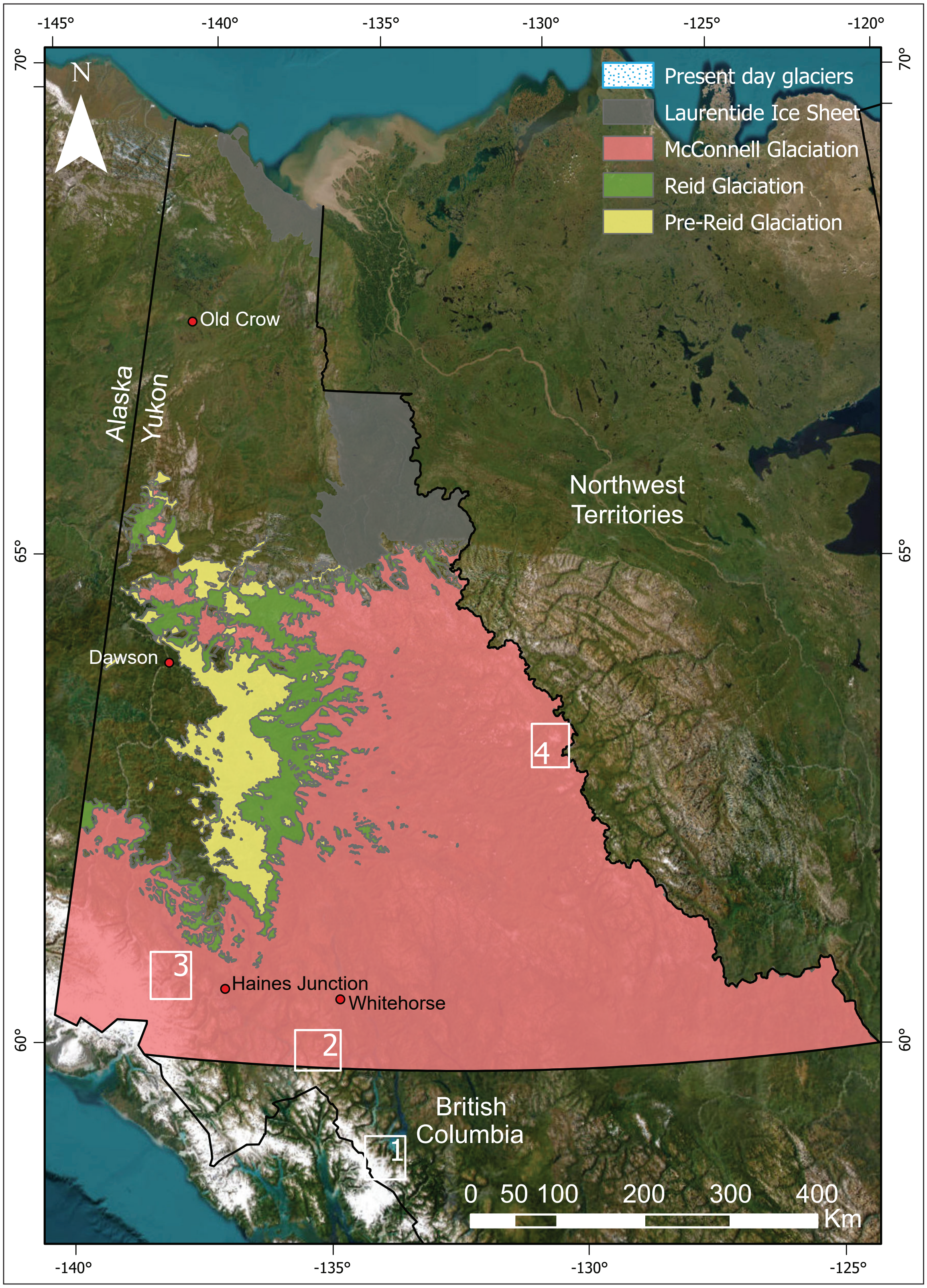

Figure 1. *Overview of glacial limits of Yukon and locations of selected study sites discussed in text:* ***(1)*** *Llewellyn Glacier, see Figure 2;* ***(2)*** *Wheaton and Radelet glaciers, see Figure 3;* ***(3)*** *Kaskawulsh Glacier, see Figure 8;* ***(4)*** *Keele Peak glaciers, see Figure 9. Glacial limits are modified from Duk-Rodkin (1999) based on updated mapping (Bond and Lipovsky, 2010; Cronmiller et al.,2018; Kennedy and Ellis, 2020; Lipovsky and Bond, 2022).*

Over the last two decades, glacier area and mass loss have accelerated in most areas of the world (Hugonnet et al., 2021). Western Canada and the USA, which have a combined glacierized area of 14 524 km^2, had a mass loss of 7.6 ± 1.7 gigatonnes per year between 2000 and 2019 and a mean thinning rate of 0.62 ± 0.11 m per year (Hugonnet et al., 2021). Clarke et al. (2015) estimate that glacier ice volume in western Canada will be diminished by 70 ± 10% by the end of the century, based on 2005 glacier volumes. The main driver of this accelerated mass loss is rising global temperatures, while some of the regional variation can be explained by changes in precipitation (Hugonnet et al., 2021).

Methodology

Terminus and volume change

We used satellite imagery to track glacier terminus change at 5-year increments between 1986 and 2021. Landsat 4, 5, 7 and 8, and Sentinel 2A imagery was sourced from the United States Geological Survey (USGS) Earth Explorer. The imagery was visualized in ArcGIS Pro and shapefiles were created for each of the glaciers selected for monitoring. Representative glaciers from each of the different glaciated regions of Yukon were selected for analysis. The glaciers selected range greatly in size — from the Kaskawulsh Glacier, which had an area of 1122.26 km^2 in 2021, to Wheaton Glacier, which had an area of only 0.71 km^2 in 2021.

Glacier extents were delineated for each 5-year increment — 1986, 1991, 1996, 2001, 2006, 2011, 2016 and 2021. Delineations were completed in ArcGIS Pro using satellite imagery, and hillshade maps for areas where glacial limits were not visible on the satellite imagery. Little Ice Age (LIA) extents were delineated using Landsat, Sentinel and Maxar imagery. LIA extents were only digitized at the termini because up-glacier lateral LIA limits are difficult to delineate due to degradation from slope movement on valley walls. Once all glacial extent features were digitized, the average retreat was measured at several points along the terminus in ArcGIS Pro to calculate change from LIA–2021, 1986–2021, and for each of the three decades between 1991 and 2021; the areal rate of retreat per year was also calculated. LIA dates for smaller glaciers were estimated from nearby known larger glacier LIA dates (e.g., Llewellyn, Donjek and Kaskawulsh).

Glacier surface elevation change maps were made using data from Hugonnet et al. (2021). The digital elevation models (DEMs) used to create these elevation maps were generated from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) stereo imagery, as well as ArcticDEM (Hugonnet et al., 2021). These elevation changes represent volume gain/ loss throughout the glacier at a resolution of 100 m (Hugonnet et al., 2021).

Field surveys

Helicopter and ground-based field surveys were conducted at Wheaton and Radelet glaciers on June 15, 2004, and September 19, 2022. An overview flight of the region was also completed to collect notes and photographs of other minor glaciers and ice patches in the Wheaton, Takhini and Bennet Lake watersheds. During ground surveys, photos of the glaciers were taken at cairns built in 2004 at the 1995 and 2004 terminus locations. The 1995 terminus locations were determined from air photographs (flight line A28240). New cairns were constructed at the 2022 termini locations. Drone surveys of both glaciers captured oblique photos for visual comparison as well as a systematic grid of nadir photos for use in future photogrammetric volume change analyses.

The current state of glaciers

Upper Yukon River headwaters region

Llewellyn Glacier area

Llewellyn Glacier terminates at the southern end of Atlin Lake in British Columbia, and is a major source of water draining into the headwaters of the Yukon River. Llewellyn is the largest of the glaciers that drain into the upper Yukon River, and contains at least half of the total ice volume in the upper Yukon River basin (Northern Climate Exchange, 2014), with a total area of about 464.75 km^2 in 2021. By that same year, the glacier terminus had retreated an average of 2.58 km from its LIA maximum, which occurred some time in the seventeenth century (Clague et al., 2010; Fig. 2).

Over the last three decades, the glacier retreat has accelerated. Llewellyn Glacier retreated 0.39 km between 1991 and 2001, 0.41 km between 2001 and 2011, and 0.66 km between 2011 and 2021 (Fig. 2).

Other glaciers in the headwaters of the Yukon River include Willison Glacier, which is located approximately 10 km northwest of Llewellyn Glacier, and Fantail Glacier, which is approximately 65 km northwest of Llewellyn Glacier. Both glaciers drain into Tagish Lake, are similar in size, but smaller than Llewellyn Glacier. Since the LIA, the terminus of Willison Glacier has retreated 4.13 km, while Fantail Glacier retreated 4.03 km. Similar to Llewellyn Glacier, the amount of retreat at Fantail Glacier increased each decade from 1991–2021. Between 2011 and 2021 the glacier retreated 0.93 km, while between 2001 and 2011 it retreated 0.54 km, and between 1991 and 2001 it retreated 0.23 km. This pattern is not the same at Willison Glacier, which retreated very similar distances over all three time periods: 0.24 km between both 1991 and 2001, and 2011 and 2021; and 0.21 km between 2001 and 2011.

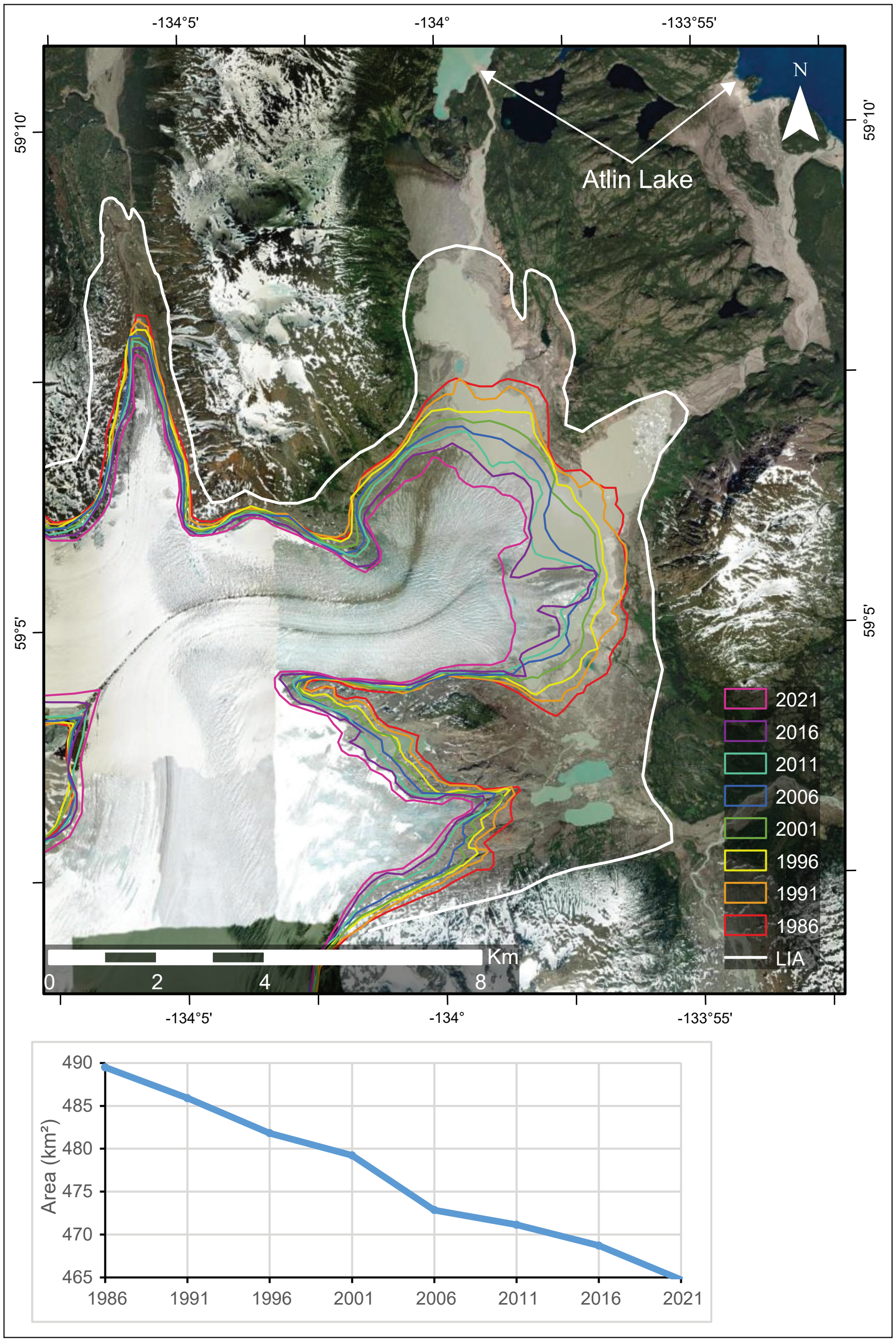

Figure 2. *Change in the areal extent of the Llewellyn Glacier, LIA to 2021. Graph depicts change in total glacier area. Satellite imagery from 2018.*

Wheaton River Basin

Meltwater from the Wheaton River glaciers also feed the upper Yukon River system. Two of the glaciers we studied in this area are the Wheaton Glacier and Radelet Glacier (Fig. 3). These two glaciers are a good representation of many of the glaciers in the area – small alpine glaciers that have retreated significantly and now cover an area of less than 1 km^2. The retreat of these glaciers, however, does not seem to follow the same pattern, despite being in very close proximity to each other. Wheaton Glacier, which is the larger of the two, has retreated 1.96 km since the LIA. Between 1991 and 2011, the Wheaton retreated 0.12 km, but only retreated 0.09 km between 2001 and 2011, and the greatest amount of retreat (0.28 km) occurred in the most recent decade. Previous work by Church and Clague (2009) found that in 2009, 92% of the mass loss since the LIA had occurred since 1948, again suggesting an acceleration in recent decades. They found that the main cause of mass loss was the increase in air temperatures, and if this warming trend continues the glacier will likely disappear within the century. At Radelet Glacier, the least amount of retreat (0.08 km) occurred during this most recent decade, while more retreat occurred during the previous two decades (0.14 km between 2001 and 2011, and 0.13 km between 1991 and 2001).

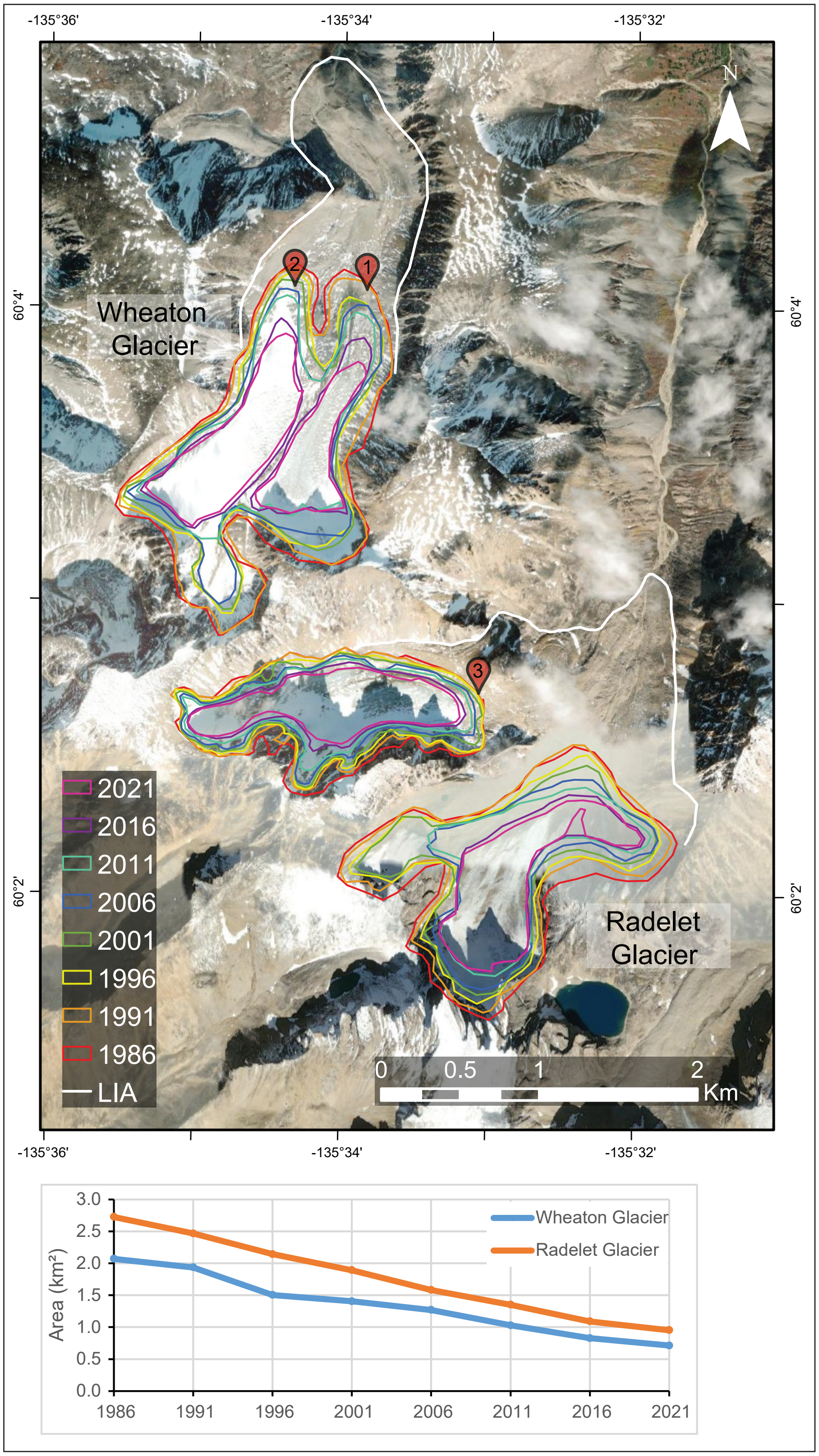

Figure 3. *Change in the areal extent of Wheaton and Radelet glaciers, LIA to 2021.* ***(1)*** *Location of photos taken in Figure 4;* ***(2)*** *location of photos taken in figure 5;* ***(3)*** *location of photos taken in figure 6. Satellite imagery from 2012.*

The Yukon Geological Survey established photo-monitoring stations at Radelet and Wheaton glaciers in 2004 that were reoccupied in 2022. Figures 4, 5 and 6 are photos taken from the same location to show the change in glacier extent over nearly 20 years. Figure 4 is the eastern lobe of the Wheaton Glacier, and Figure 5 is the western lobe of the Wheaton Glacier, which had retreated about 375 m and 310 m, respectively, between 2004 and 2021. Based on the area delineated from the satellite imagery, the Wheaton Glacier was 1.41 km^2 in 2001 and 0.71 km^2 in 2021, which is a loss of half the area of the glacier in 20 years. Figure 6 is the western side of Radelet Glacier, which covers a much smaller area than it did in 2004, and the ice thickness has visibly lowered across the entire glacier. The area of Radelet Glacier was 1.89 km^2 in 2001 and 0.95 km^2 in 2021, which is again a decrease of almost half the glacier area.

Figure 4. *East Wheaton Glacier in June 2004 (left) and September 2022 (right). Arrows point to the cairn erected in 2004 at the 1995 terminus location. The approximate 2004 extent is delineated on the 2022 photo (dashed line). Seasonal snow is present in the June 2004 photograph; however, it is not likely to significantly increase the apparent glacier extent.*

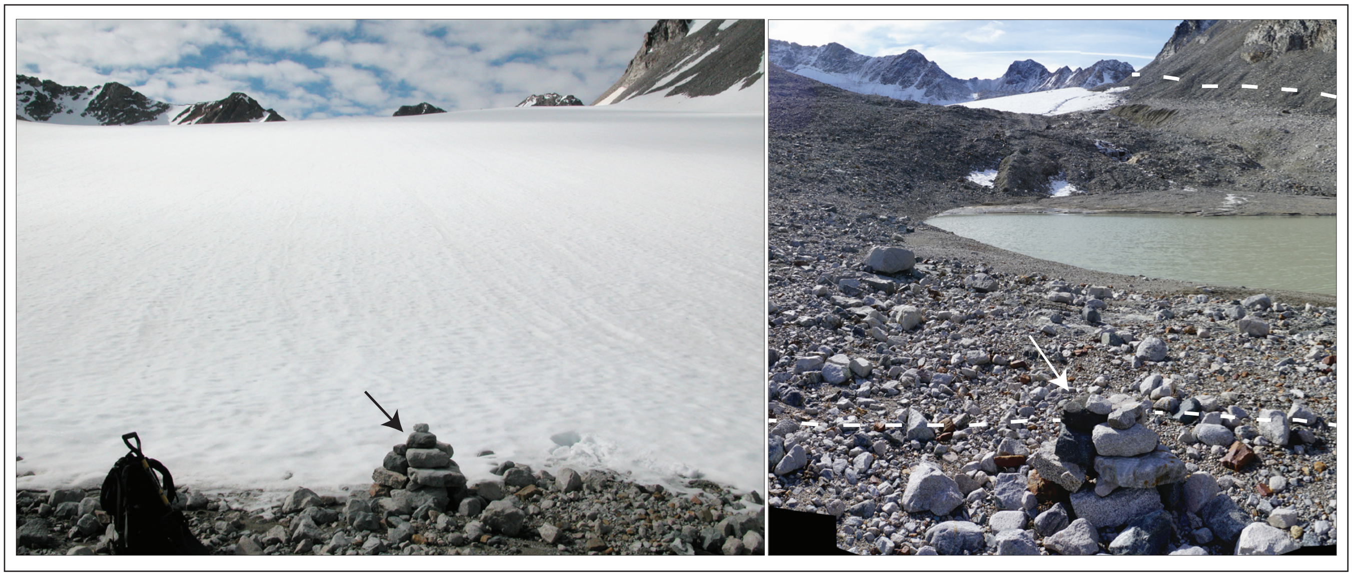

Figure 5. *West Wheaton Glacier in June 2004 (left) and September 2022 (right). The approximate 2004 extent is delineated on the 2022 photo (white line). Seasonal snow is present in the June 2004 photograph; however, it is not likely to significantly increase the apparent glacier extent. Note the Proglacial Lake present in 2022 was covered by ice in 2004.*

Figure 6. *West Radelet Glacier in June 2004 (top) and September 2022 (bottom) showing considerable retreat and thinning. Seasonal snow is present in the June 2004 photograph; however, it is not likely to significantly increase the apparent glacier extent.*

Many other small glaciers and perennial ice patches exist throughout the Wheaton River basin. During the September 2022 regional overview flight, névé was absent from nearly all of the observed glaciers or ice patches despite having 180% the typical snowpack in the Southern Lakes region (Government of Yukon, 2022) indicating a net mass loss in 2022. The lack of snowpack on these glaciers also suggests that the equilibrium line altitude has surpassed the highest point of the glacier.

St Elias Mountains region

The St. Elias Mountains are Canada's highest mountains, and contain the world's largest non-polar icefield (https://www.pc.gc.ca/en/pn-np/yt/kluane/nature/geomorph). The St. Elias Mountains are one of the few areas of the world that host a cluster of surge-type glaciers (Clarke et *al*., 1986), which are glaciers that undergo cyclical periods of rapid advance, followed by a long period of retreat. For this reason, surge-type glaciers can present differently in area change.

The only surge-type glacier that was a part of our study was the Donjek Glacier (Fig. 7), which is located in the St. Elias Mountains and drains into the Donjek River. Since 1986, the Donjek Glacier has surged three times: 1988–1990, 2000–2002 and 2012–2014 (Kochtitzky et *al*., 2019). During each of these surge events, the maximum terminus position has been farther back than the one previous, indicating a negative mass balance (Kochtitzky et *al*., 2019).

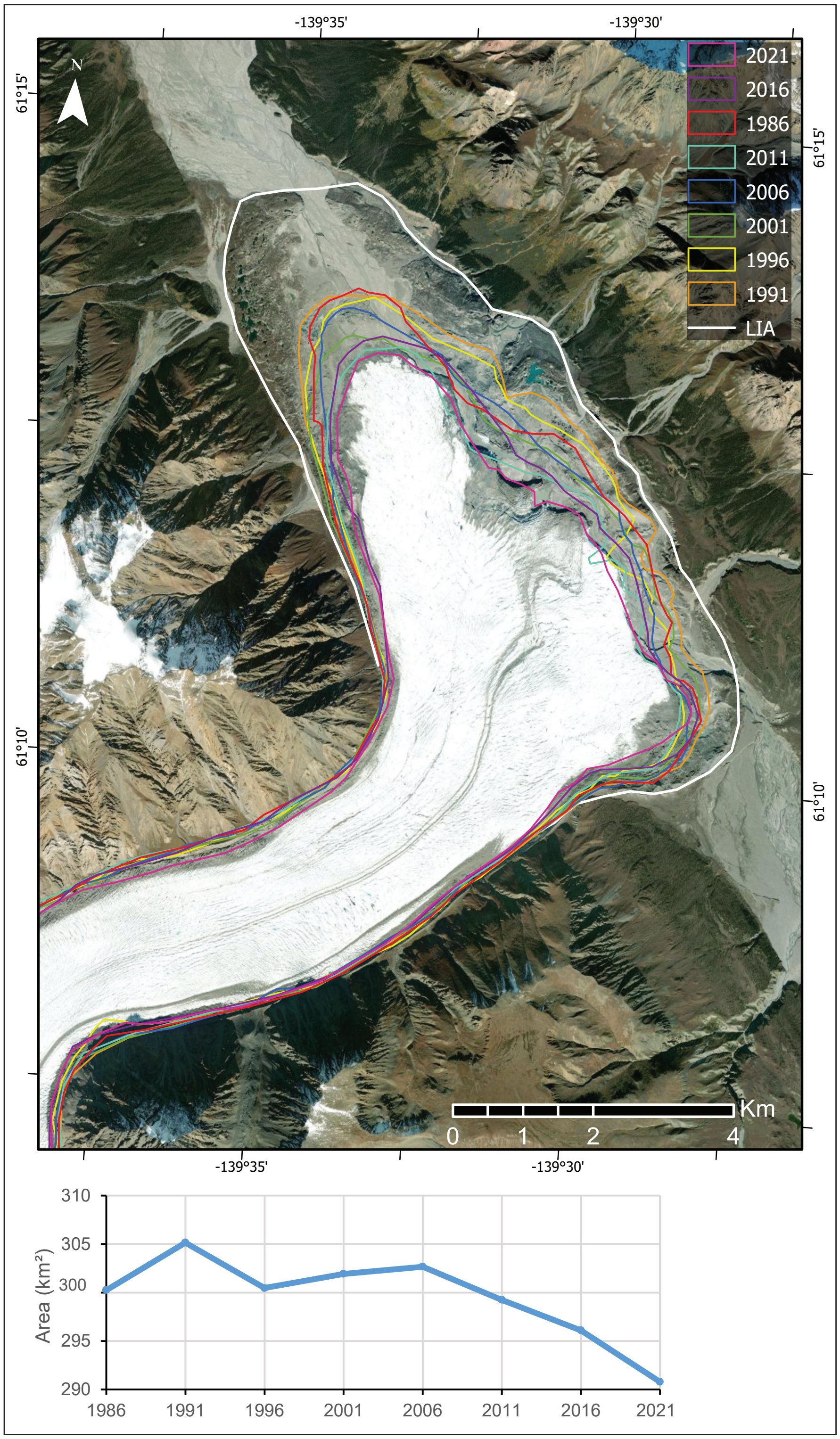

Figure 7. *Change in areal extent of the Donjek Glacier terminus, LIA to 2021. Graph depicts change in total glacier area. Satellite imagery from 2019.*

Another large valley glacier in the St Elias Mountains is the Kaskawulsh Glacier (Fig. 8), which is not a surge-type glacier. The Kaskawulsh has retreated 2.18 km since the LIA in the mid-1750s (Reyes et al., 2006). Between 1991 and 2001 the terminus retreated 0.2 km, whereas between 2011 and 2021, it retreated 0.33 km. The retreat of the Kaskawulsh Glacier has had significant recent impacts on the surrounding area. In 2016, the glacier retreated far enough that meltwater formerly draining northwards into Slims River (A’ ąy Chù’) and Kluane Lake (Łù’ àn Mân) was rerouted eastward into the Kaskawulsh and Alsek river system. Prior to 2016, meltwater from the Kaskawulsh Glacier was the main source of water for Kluane Lake, and lake levels have since dropped approximately 2 m (Shugar et al., 2017). A recent study suggests that as the Kaskawulsh Glacier adjusts to current mass imbalances it will see a terminus retreat of approximately 23 km over the next century and loss of 15% of its total volume under current climate conditions (Young et al., 2021).

Keele Peak area, Mackenzie Mountains

The Keele Peak area in the Mackenzie Mountains contains small alpine glaciers, four of which were included in our study. These glaciers ranged in size from 5.58 km^2 to 0.6 km^2 in 2021. Smaller alpine glaciers like these have different retreat patterns than large valley glaciers, which tend to retreat more at the terminus with much less change farther up-glacier. For example, the largest of the four glaciers studied, Mackenzie glacier 1 (Fig. 9), retreated

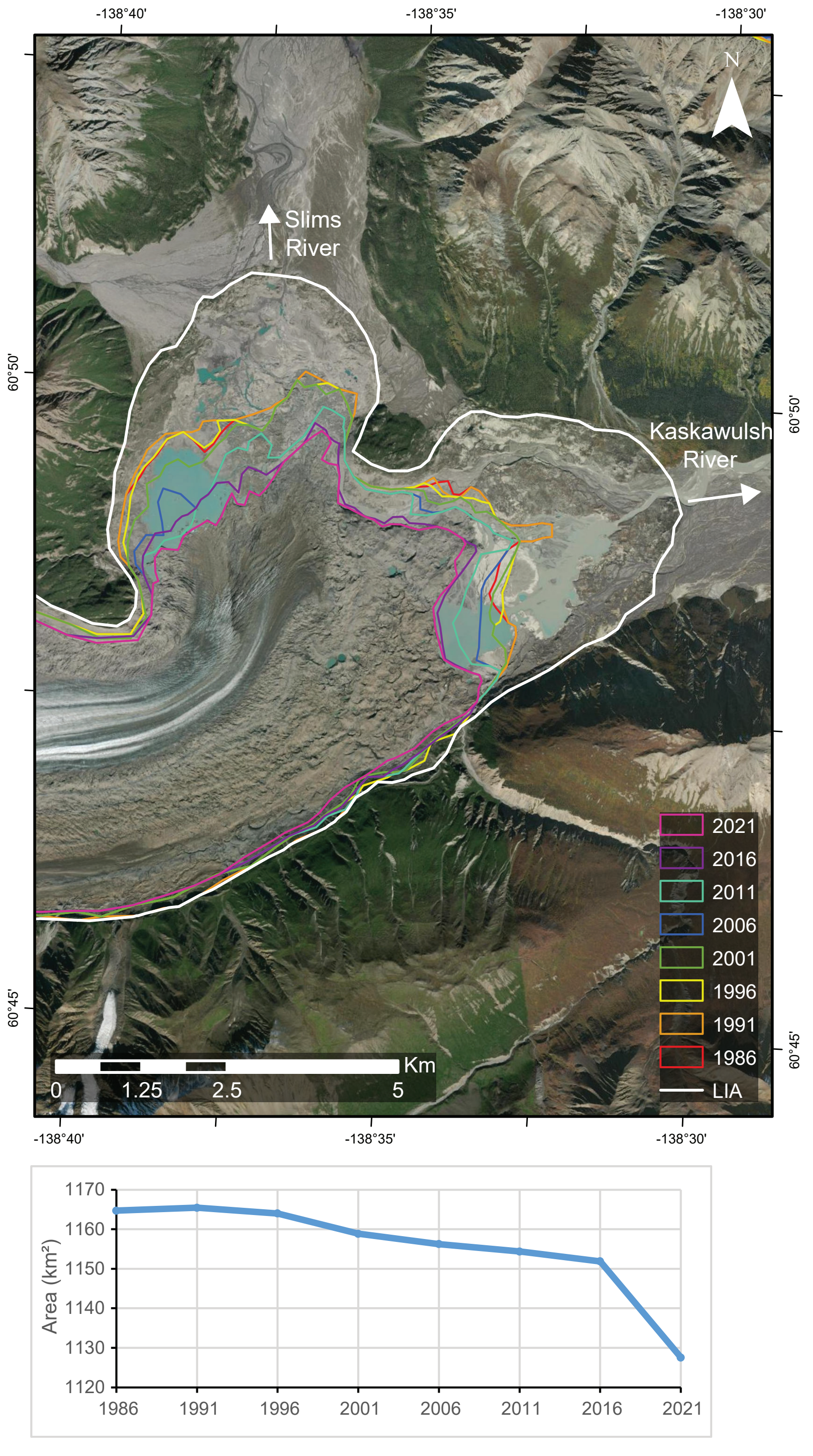

***Figure 8.** Change in areal extent of the Kaskawulsh Glacier terminus, LIA to 2021. Graph depicts change in total glacier area. Satellite imagery from 2019.*

only 0.33 km at the terminus between 1986 and 2021, which was the least of all the four glaciers. Its areal extent, however, dropped by 1.62 km^2 or 22.5%, during the same period which was the highest change in areal extent for the same four glaciers. One of the intermediate sized glaciers, Mackenzie glacier 2 (2.01 km^2 in area in 2021, Fig. 9), retreated 1.13 km during the same period. Mackenzie glacier 3 was the smallest glacier in 2021, at only 0.6 km^2, while Mackenzie glacier 4 had an area of 2.25 km^2. Both these glaciers retreated more than Mackenzie glacier 1, but less than Mackenzie glacier 2. Mackenzie glacier 3 retreated 0.54 km between 1986 and 2021, while Mackenzie glacier 4 retreated 0.99 km in that time.

Glacier thickness changes

Glacier surface elevation data from Hugonnet *et al.* (2021) were used to determine approximate changes in glacier thickness between 2000 and 2019. Figure 10 shows part of the upper Yukon River watershed, including Llewellyn, Willison and Fantail glaciers. All glaciers in this region have experienced the most thinning at their fronts, with an average thinning rate of about 5 m/year over 20 years. Thinning rates at higher elevations are generally less than 3 m/year.

Figure 11 shows the glaciers that drain into the Donjek River. More elevation gain occurred on the glaciers in this region than for glaciers in the upper Yukon River watershed. This is because several glaciers in this region are surge-type.

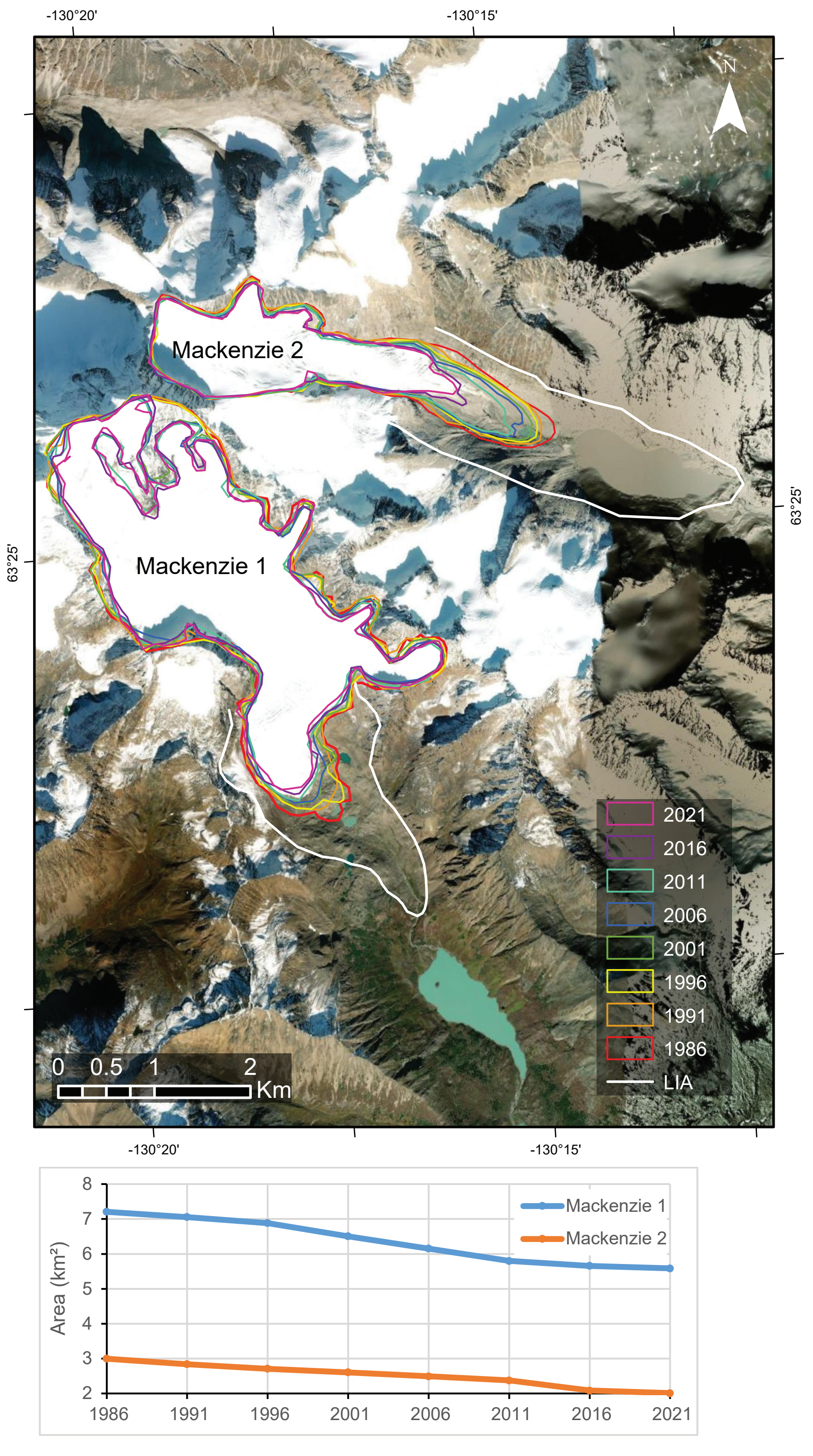

Figure 9. *Change in areal extent of Mackenzie glaciers 1 (south) and 2 (north), LIA to 2021. Satellite imagery from 2014.*

Before a glacier surges it will accumulate mass in one area, and then redistribute that mass downwards during the surge. For example, the Steele Glacier (Fig. 10) thinned significantly (up to 9 m/year) in the upper part of the glacier, but thickened up to 7 m/year in the middle of the glacier. A similar but less pronounced pattern also occurred at the Donjek Glacier. These surging glaciers still exhibit prominent thinning at their fronts, similar to the pattern for the upper Yukon River watershed glaciers. Smaller alpine glaciers, such as those in the Mackenzie Mountains, have thinned less than the larger glaciers of the upper Yukon and St. Elias Mountains. These smaller glaciers only thinned approximately 2 m/year between 2000 and 2020, even at their termini.

Previous work has been done by Yukon University and Yukon Energy Corporation (YEC) to assess changes to glaciers in the upper Yukon River watershed. YEC used data from NASA's Gravity Recovery and Climate Experiment (GRACE) to estimate glacier mass loss in northern British Columbia, southwestern Yukon and southeastern Alaska (Doumbia et al., 2020; Rousseau et al., 2020). This study found an average mass loss of about 40.82 Gt/year between 2002 and 2017 (Rousseau et al., 2020). Hugonnet et al. (2021) estimated a mass loss of about 66.7 ± 10.9 Gt/year for Alaska from 2000–2019; however, their study area covers the entirety of Alaska with a glacierized area of 86 725 km^2, while the YEC study area is much smaller, at only 55 000 km^2 glacierized area. Yukon University assessed the elevation change of glaciers between 1987 and 2000 using digital elevation models (Northern Climate Exchange, 2014).

Figure 10. *Glacier surface elevation change from 2000 to 2019 on the Canadian side of the Juneau Icefield, upper Yukon River headwaters. Data from Hugonnet et al., 2021.*

Their study found a surface lowering (thinning) of 80 to 100 m (*i.e.*, an average rate of 6.15 m/yr) at the termini of many of the larger glaciers in the upper Yukon River watershed. Hugonnet et *al.* (2021) data for the 2000-2005 period show a surface lowering of up to 6 m/year at the termini of some of the larger glaciers in the same area, including Fantail and Llewellyn glaciers. The thinning rates determined from both studies agree closely despite using contrasting methods.

Discussion/Impacts

Almost all the glaciers in our study have been retreating since 1986, the only exception being Donjek Glacier which has undergone three surge events since that time. The surge events at the Donjek Glacier have resulted in terminus advance over short periods, but the long-term mass balance trend is still negative (Kochtitzky et *al.*, 2019). Llewellyn Glacier and Fantail Glacier have both

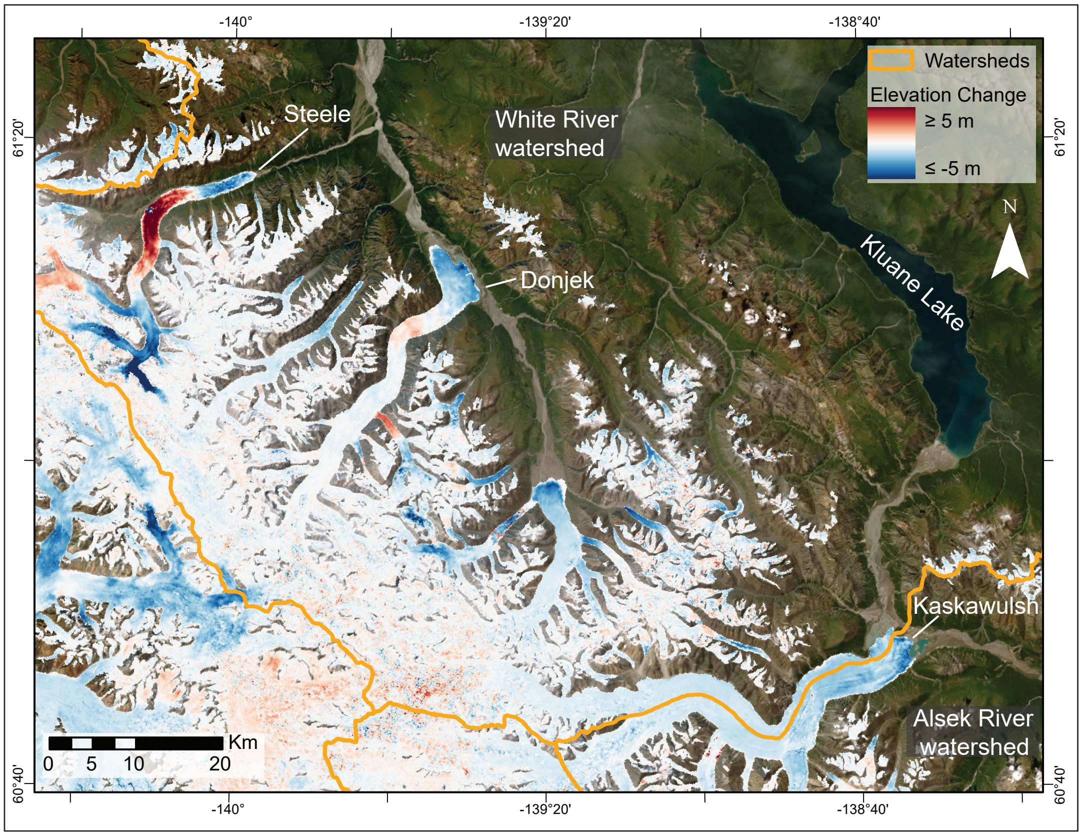

Figure 11. *Glacier surface elevation change from 2000 to 2019 in the White River watershed. Data from Hugonnet et al., 2021.*

experienced accelerated terminus retreat over the last three decades. Willison Glacier, which is located in the same region, has remained consistent in its retreat over this time. Donjek Glacier has slowed its terminus retreat in the three decades since 1991, but has also surged two times during that period, which advanced the terminus of the glacier. Kaskawulsh Glacier terminus retreat accelerated between 1991 and 2001, and 2001 and 2011, but the retreat in the most recent decade was very similar to that of 2001–2011. The glaciers on Keele Peak had contrasting retreat patterns, despite their close proximity and similar size. Mackenzie glacier 1 decelerated in terminus retreat over the last three decades, while Mackenzie glacier 2 accelerated. This same contrast was seen at the Wheaton Valley glaciers (Wheaton Glacier and Radelet Glacier). Wheaton Glacier has more than doubled its retreat from the first decade to the most recent one, while Radelet Glacier has slowed retreat. It is likely that some of the slow down in retreat at Radelet Glacier is due to the remaining ice being entirely within cirques, which provide increased shading from solar radiation and have higher altitude, which favours ice preservation due to topographic configuration (cf., DeBeer and Sharp 2009). As stated earlier, the Wheaton Valley glaciers aerial extent dropped by about 50% in the 20 years between 2001 and 2021; however, this amount of area change was not observed at the Keele Peak glaciers, which are small alpine glaciers similar to Wheaton and Radelet glaciers. Although there has not been universal acceleration of terminus retreat at all glaciers in our study (Table 1), there has been a significant acceleration in elevation loss over the last two decades. Average glacier elevation loss was calculated for four of the major watersheds in Yukon (Table 2), and all four had an increase of at least 300% from the 2000–2010 to the 2010–2020 period.

Table 1. *Decadal area and terminus change by glacier.*

	Area Change (km²)			Terminus Retreat (km)			
Glacier	**1991-2001**	**2001-2011**	**2011-2021**	**LIA-1991**	**1991-2001**	**2001-2011**	**2011-2021**
Kaskawulsh	-6.60	-4.49	-26.79	-1.30	-0.2	-0.35	-0.33
Donjek	-3.22	-2.68	-8.47	-0.69	-0.32	-0.24	-0.15
Wheaton	-0.53	-0.38	-0.32	-1.47	-0.12	-0.09	-0.28
Radelet	-0.58	-0.54	-0.40	-0.94	-0.13	-0.14	-0.08
Llewellyn	-6.67	-8.07	-6.41	-1.12	-0.39	-0.41	-0.66
Willison	-1.96	-1.44	-1.68	-3.44	-0.24	-0.21	-0.24
Fantail	-1.14	-2.19	-2.14	-2.33	-0.23	-0.54	-0.93
Mackenzie 1	-0.55	-0.71	-0.21	-0.54	-0.14	-0.13	-0.06
Mackenzie 2	-0.24	-0.23	-0.36	-2.01	-0.1	-0.31	-0.72

Table 2. *Average glacier elevation change (m/year) by watershed (data from Hugonnet et al. 2021).*

Watershed	**2000–2010**	**2010–2020**
White River	-0.09	-0.41
Alsek River	-0.37	-1.43
Tagish and Atlin Lake	-0.13	-1.43
Hess (Keele Peak)	-0.02	-0.72

Short-term negative glacier mass balance trends may cause short-term increases in summer water flows generated by increased glacial meltwater runoff resulting from warmer air temperatures. However, in the long term, continued negative mass balance will eventually result in glaciers becoming too small to produce increased amounts of meltwater (Barnett et *al.*, 2005). Stahl and Moore (2006) conducted a study on the effects of glacier cover on streamflow in British Columbia. They found mostly declining stream flows in glacier-fed streams, with exceptions in northwestern BC and the northern Rockies. This suggests that the larger glaciers in northern BC have not yet reached their maximum discharge levels, while glacier fed catchments in southern BC have already passed this threshold, and will likely continue to decline (Stahl and Moore, 2006). This coincides with Fleming and Clarke's (2003) study, which documented increasing annual flow volumes for glacier-fed rivers in southwestern Yukon due to increased meltwater production from larger glaciers similar to those in northwestern BC. "Peak water" is the term used for the maximum discharge reached as glacier meltwater volumes increase with continued glacier recession, followed by decreased meltwater discharge as the volume of water stored in the glacier depletes. Huss and Hock (2018) modelled glacier meltwater runoff changes up to the year 2100 in all large drainage basins outside of Greenland and Antarctica, including the Yukon River and Alsek River basins. Their study found that in the year 2017, peak water had already been reached in 45% of the basins, while runoff is expected to continue rising past 2050 in 22% of basins (Huss and Hock, 2018). Basins with large glaciers and glacierized area, such as the Yukon and Alsek watersheds, were modelled to reach peak water by the end of the 21st century, while basins with smaller glaciers could reach peak water within the next decade (Huss and Hock, 2018). The YEC project that peak water for the upper Yukon River watershed will occur around 2040 (Rousseau et *al.*, 2020).

Glacial fed streams and rivers also experience longer, larger and later spring high water, and have higher fall and winter base flows than rivers fed solely by snow (Fleming, 2005), allowing them to compensate for low precipitation or drought years. In 2020, Yukon was powered by 86% renewable energy primarily derived from three hydroelectric power stations in Whitehorse, Aishihik and Mayo (Yukon Energy, 2022). The Whitehorse hydro power station is in part supplied by runoff originating from glaciers in the upper Yukon River basin. Modelling completed by the YEC projects an increase in annual runoff until ~2040, followed by a steady decrease until 2070 (Rousseau et *al.*, 2020). This is attributed to glacier mass loss in the region and the annual runoff at the end of 2070 is estimated to be similar to 1980 values (Rousseau et *al.*, 2020).

Declining summer flows will also affect stream temperatures, turbidity and water chemistry. This may affect fish and downstream habitats (Milner et *al.*, 2017; McKnight et *al.*, 2021), as will large-scale changes to basin geometry or rerouting of stream and river systems caused by glacial retreat, as occurred at the Kaskawulsh Glacier in 2016 (Shugar et *al.*, 2017). Natural hazards following glacier recession also include mass movements and ice avalanches from steep mountain glaciers (*e.g.*, Mt. Steele; Lipovsky et *al.*, 2008), and the formation of more and larger proglacial lakes, which may be subject to outburst flooding (Milner et *al.*, 2017; Painter, 2021; Shugar et *al.*, 2020).

Future Work

Although glacier area change and terminus retreat rates are indicators of glacier health, mass and elevation changes provide a more comprehensive understanding of glacier change. Long-term high-resolution mass balance monitoring at select glaciers in Yukon, particularly in the upper Yukon River basin, would be beneficial to better understand glacier mass change and potential impacts. Remote sensing methods with select field validation are likely to be the most economically and environmentally sustainable approaches to this. In Yukon, one of the main concerns with glacier mass wasting is consequences for hydropower, which is currently the territory's main source of renewable energy. In order to have an improved understanding of the role that glaciers play on the territory's water resources, particularly in the upper Yukon River basin, monitoring of water flow, temperatures, chemistry and timing should be established.

Summary and Conclusions

On a global scale, there has been a significant trend of glacier recession in the recent decades, which is predicted to continue through the end of the century (Hock et *al.*, 2019; Hugonnet et *al.*, 2021). Yukon and northern BC have been no exception to this trend, as all glaciers in this study have been retreating since the late 1980s. Despite snowpack in the Wheaton basin greatly exceeding average depths during the winters of 2021 and 2022, net mass losses still occurred in the following melt seasons due to increasingly warm summers. Glacier runoff increases as glaciers continue to recede, but continued mass loss will inevitably result in diminished runoff and consequently diminished contribution to the upper Yukon River, which supplies the Whitehorse hydropower station. Glacier retreat and mass wasting will have an effect on stream and river characteristics, such as temperature and turbidity changes, which will in turn have an impact on fish populations (Milner et *al.*, 2017; McKnight et *al.*, 2021). Glacier retreat has also contributed to an increase in certain geohazards such as glacial lake outburst floods and mass movements (Milner et *al.*, 2017; Shugar et *al.*, 2020) which should be considered in regional land use planning.

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