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Glacier Cover Change Assessment of the Columbia Icefield in the Canadian Rocky Mountains, Canada (1985–2018)

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Abstract: Meltwater from glaciers makes significant contributions to general streamflow and provides water for flora and fauna. Continuous glacier monitoring programs enhance our understanding of the impacts of global warming on glaciers and their topographical features. The objective of this study is to measure spatial and temporal changes in Canada's Columbia Icefield glaciers. This study uses Landsat (TM 5 and OLI) images to delineate glacier extents in the Columbia Icefield between 1985 and 2018. The study also analyzes the retreat of the Athabasca, Castleguard, Columbia, Dome, Saskatchewan, and Stutfield Glaciers. The total area covered by the Icefield in 1985 was 227 km^2. By 2018, the Icefield had lost approximately 42 km^2 of its area coverage, representing 18% of its previous coverage. All glaciers in the study region retreated and decreased in area over the study period. The pattern observed in this study is one of general ice loss in the Columbia Icefield, which mirrors patterns observed in other mountain glaciers in Western Canada.

Keywords: glaciers; Landsat; mass balance; machine learning; remote sensing; global warming; Columbia Icefield

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1. Introduction

Glaciers are a notable part of the cryosphere and play an important role in climate studies [1,2]. Glaciers adjust their size as a response to changing climatic conditions, which make them good indicators of climate change. Glaciers remain the largest reservoir of freshwater on Earth, serving more than 1.3 billion people [3]. Meltwater, particularly from mountain glaciers, makes significant contributions to general streamflow, especially in late summer when there are warm periods with dry weather [4,5]. Surface runoff from glaciers during summer regulate stream temperature, making it conducive for irrigation, tourism, industry, hydro power, domestic consumption, and to support aquatic life [6,7]. Like other mountain glaciers, the Columbia Icefield (referred to as the "mother of rivers") in the Canadian Rockies serves as a significant water resource as its meltwater feeds the Columbia, Athabasca, North Saskatchewan, and Fraser River systems [8]. Glacier run-off in the region is heavily relied upon for hydroelectric power generation in parts of British Columbia. Mass wastage of these glaciers can cause increased volumes of late summer discharge, which could lead to long-term loss of natural fresh water. A glacial lake outburst flood (GLOF) could lead to rapid discharge, which is mostly catastrophic to surrounding regions [9]. Due to the important role these mountain glaciers play in supplementing streams required for human and aquatic consumptions, it is imperative to monitor them periodically. Studies of these mountain glaciers are necessary to understand their response to climate change and to predict the long-term impacts on water availability and global sea-level rise hazard preparedness. The Columbia Icefield also serves as one of the most visited tourist sites in North America; hence, consistent Icefield monitoring is key for decision-making regarding hazard risk assessments that may be associated with glacier cover change [10].

Beginning in the 1980s, the need to monitor these glaciers led to federal mapping, which commenced as part of Canada's contribution to the International Hydrological Decade.

Glacier studies in the region have progressed over the years in the 21st century [10–12]. Glaciologists in the area relied on the use of photogrammetric methods for glacier studies due to the size and remoteness of the glaciers [13,14]. These mappings focused on glacier length while a few included glacier thickness and width. The surveys were limited to easily accessible glaciers (Athabasca, Columbia, and Saskatchewan) with smoother features than others in the Canadian Cordillera. Subsequently, monitoring of the Athabasca and Saskatchewan Glaciers expanded to include mapping of glacier terminus changes, elevation, volume changes, and mass balance [15]. The Peyto Glacier, located in the Banff National Park, has the longest record of mass balance [16]. The Columbia Icefield, like other mountain ice in the 20th century, has seen an accelerated wastage of glacier ice [17]. Recent studies by Tennant and Menounos [15] reported that the Icefield retreated by an average of 1150 ± 34 m with an average thinning of 49 ± 25 meter water equivalent (m.w.e.) at a rate of -0.6 ± 0.3 m w.e.$\cdot$a^{-1} between 1919 and 2009. Shrinkage reported was 2.4 ± 0.2 and total area lost was 59.6 ± 1.2 km^2 (23 ± 5%) at a rate of -0.6 ± 0.3 m.w.e. a^{-1}. These rates are, however, not uniform across the Icefield due to differences in size, topographical features, and surface cover. Remote sensing of glaciers provides a robust way to monitor the health of these glaciers which is assessed via changes in their area, length, volume, and mass balance over a specific period.

The objective of this study is to use Landsat satellite imagery between 1985 and 2018 in combination with high resolution images to measure spatial and temporal changes in the Columbia Icefield.

2. Study Area

The Columbia Icefield is the largest icefield in the Canadian Rockies lying partly in the northwestern tip of Banff National Park and partly in the southern end of Jasper National Park (Figure 1). Meltwater from the Athabasca glacier flows into the Athabasca River and then into Lake Athabasca. Then it flows by the Slave River, through the Mackenzie River, and finally into the Arctic Ocean [18]. Meltwater from the Saskatchewan Glacier flows into Saskatchewan River and crosses the Alberta, Manitoba, and Saskatchewan provinces into the Hudson Bay and finally reaches the Atlantic Ocean. Runoff from the Columbia Glacier flows via the Columbia and Fraser Rivers into the Pacific Ocean. The Icefield comprises 25 glaciers and may be either of individual ice bodies or glacier outlets based on glacial drainage [19].

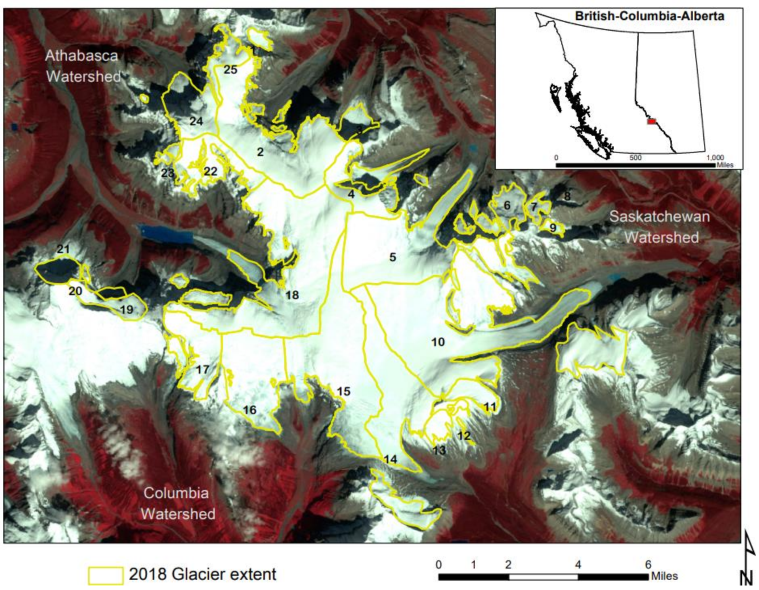

Figure 1. Study area. Landsat TM 5 scene obtained on 10 September 1999 showing the Columbia Icefield.

The six major glacier outlets include Stutfield to the north, Dome to the northeast, Athabasca and Saskatchewan to the east, Castleguard to the south, and Columbia to the West. The main glacier body is steep, which drops off through the lower glacier tongues into deep canyons. The region is also characterized by lakes and thick, low-level forests in the fringing valley areas. Its elevation ranges between 1000 and 3700 m a.s.l. [14].

The highest peaks of the Columbia Icefield are Mt. Athabasca (3491 m) and Mt. Columbia (3745 m). The lower regions experience the development of alpine tundra in regions above ~2250 m a.s.l., creating the Engelmann Spruce–Subalpine Fir ecosystem [15]. The region has an average annual temperature of –4.0 °C and an annual snow precipitation of 1277 mm between 1919 and 2009 [15]. The region's climate is characterized by cyclonic storms which occur because of maritime polar air masses from the west (between September and June) and continental polar air masses from the east in winter [15].

3. Data

3.1. Satellite Imagery

We utilized two rectified Landsat Thematic Mapper 5 (TM) scenes (acquired on 5 September 1985, and 8 September 1999) and one Landsat 8 Operational Land Imager (OLI) scene (acquired on 10 September 2018). Both TM and OLI bands have a nominal spatial resolution of 30 m. The visible and near-infrared (VNIR) regions make up five spectral bands with two shortwave infra-red bands. OLI has one cirrus cloud detection band, two thermal bands (TIRS), and a 15 m panchromatic band (USGS 2015). The World Reference System (WRS2) path 44 and row 24 Landsat scenes were downloaded from the USGS Earth Resources Observation and Science Center (EROS) using the USGS Earth Explorer website (https://earthexplorer.usgs.gov). The scenes covered the full extent of the Columbia Icefield with minimal cloud coverage (<20%) [20].

3.2. Reference Data

The primary reference data were glacier boundaries selected from the Northern Cordillera region collection from the Global Land Ice Measurement from Space (GLIMS) inventory [21]. GLIMS is an international initiative whose goal is to join world-wide collaborators to primarily use satellite imagery and a wide range of techniques for glacier studies and monitoring to create a comprehensive database of current extents of world glaciers. The second reference source for the manual digitization was high resolution images from Google Maps and Bing Maps™.

4. Methods

4.1. Manual Delineation

All bands were resampled to 30 m and were already projected to NAD83 UTM zone 11. For the main processing, a threshold was applied to the NDSI ratio of each year, and glacier boundaries were manually digitized. In areas where there were cast shadows, a TM3/TM5 band ratio was used to help identify ice in those areas [22] at pixel level. After the first classification, detailed digitization was done on areas that appeared to be debris-covered with guidance from Google Maps and Bing images to help identify previously mapped extents and ice in cast shadow. The glacier outlines were overlaid on the false-color composite of TM band equivalents of 543 and 321 as RGB (red, green, blue), which were created for proper identification of glacier and clouds for further corrections [23]. The resulting glacier outlines were superimposed on the respective images, and the total area of each of the glaciers in the Icefield were calculated for the three years. The change in glacier area (km^2) was calculated as the difference between the area of a previous year and the following year used in this study. Glacier retreat at the tongues of Athabasca, Stutfield, Columbia, Castleguard, Saskatchewan, and Dome were calculated as the difference between the termini in a previous study year and the termini in the following study year. Table 1 below shows the characteristics of the Icefield which was adopted from Tennant and Menounos [15].

Table 1. Characteristics and spatial extents of glaciers in the Columbia Icefield.

Glacier Id	GID_ Alias	Glacier Name	Watershed	Glacier Type	Length km	EL m a.s.l.	Elmin m a.s.l.	Elmax m a.s.l.	Slope °	Aspect
G242618E52257N	G1		Athabasca	DA	2.14024	2322	1829	2997	24	E
G242636E52211N	G2	Stutfield	Athabasca	OIA	5.48778	2730	1716	3641	22	N
G242667E52233N	G3		Athabasca	DA	2.8122	2414	2113	3104	19	N
G242700E52191N	G4	Dome	Athabasca	OIA	5.1964	2557	1985	3499	20	NE
G242719E52168N	G5	Athabasca	Athabasca	OI	8.57839	2661	1941	3630	18	NE
G242808E52190N	G7		Athabasca	D	2.39973	2707	2292	3300	24	NE
G242528E52148N	G19	Manitoba	Athabasca	DA	2.87506	2508	1707	3115	24	N
G242507E52151N	G20		Athabasca	DA	1.33019	2328	2139	2893	29	NE
G242484E52165N	G21		Athabasca	DA	2.80028	2201	2018	3009	13	N
G242588E52208N	G22		Athabasca	OI	2.78967	2904	2232	3604	27	SE
G242556E52214N	G23		Athabasca	DA	3.26222	2666	2141	3374	24	W
G242571E52227N	G24		Athabasca	DA	4.8831	2738	1776	3685	23	NW
G242604E52252N	G25		Athabasca	OIA	3.24986	2985	2251	3446	31	NW
G242790E52191N	G6	Little Athabasca	Columbia	D	2.27291	2744	2258	3301	25	N
G242690E52094N	G15		Columbia	OI	10.5525	2460	1620	3268	18	SW
G242614E52109N	G16		Columbia	O	5.114	2540	1810	3122	16	SE
G242573E52119N	G17		Columbia	OI	3.00956	2684	1767	3416	22	SW
G242657E52180N	G18	Columbia	Columbia	OI	8.96298	2738	1511	3567	22	W
G242808E52190N	G8		Saskatchewan	D	2.14288	2426	2358	2526	18	E
G242821E52181N	G9	Hilda	Saskatchewan	D	3.24571	2369	2062	2796	25	NE
G242731E52135N	G10	Saskatchewan	Saskatchewan	O	12.4949	2513	1776	3534	16	E
G242766E52115N	G11	Castleguard I	Saskatchewan	O	2.5705	2627	2325	3020	16	E
G242757E52101N	G12	Castleguard II	Saskatchewan	D	0.991545	2624	2482	2809	19	SE
G242711E52106N	G13	Castleguard III	Saskatchewan	O	1.32388	2609	2463	2762	12	SE
G242711E52106N	G14	Castleguard IV	Saskatchewan	O	10.1888	2429	1973	3031	15	SE
Mean					4.427011	2579.36	2021.8	3217.96		

D is a detached glacier, O is an outlet glacier, I is glaciers with at least one icefall, and A means the glaciers is avalanche-fed. (Glacier ID, flowshed, watershed, type, elevation, slope, and aspect adapted from GLIMS inventory).

4.2. Error Estimation

For error in glacier area, a buffer was created around each individual glacier [6], and the difference between the two polygons was calculated. The buffer method for error estimation added and subtracted a specific distance from the glacier outlines and then calculated the difference. In this study, we used the length error as the buffer distance. A detailed error analysis as laid out in the Tennant and Menounos study [6,15] was followed. The area was calculated and subtracted from the area of the digitized boundaries using the raster calculator tool in ArcGIS. The sum of each year's error was noted, and the total error in glacier change measurements was computed as:

$$E_{\Delta} = \sqrt{E_1^2 + E_2^2 + \ldots + E_n^2} \quad (1)$$

where E_{Δ} is the total error calculated, E_1^2 is the error in year one, and so on. Absolute length error was based on the combined mean horizontal RMSE and half of the resolution of the data (15 m) of a scene. Error in retreat between two years was calculated using Equation (1).

5. Results

Results from this study on glacier area and length changes indicate a significant retreat of the glaciers in the Columbia Icefield from 1985 to 2018. Each glacier experienced some amount of retreat and loss in coverage area (Figure 2). The Columbia Glacier experienced the highest absolute retreat (3.37 km) but has a lake at its terminus. The least retreated glacier was the Athabasca (0.56 km) over the study period. Mean retreat recorded for the Athabasca, Columbia, Stutfield, Dome, Castleguard, and Saskatchewan Glaciers was 1.42 km at a rate of 0.04 km·a^{-1} as shown in Table 2. Results indicate a retreat in glacier tongues of the Columbia Icefield in the period 1985–2018. All glaciers except Dome and Stutfield experienced lower retreat in 1985–1999 than in 1999–2018. The total mean among all six glaciers between the first half of the study period increased about 400% in the second half of the study period as shown in Table 2. Estimated error in retreat length was 21.6 m, which is negligible since it is less than 1 pixel size (30 m).

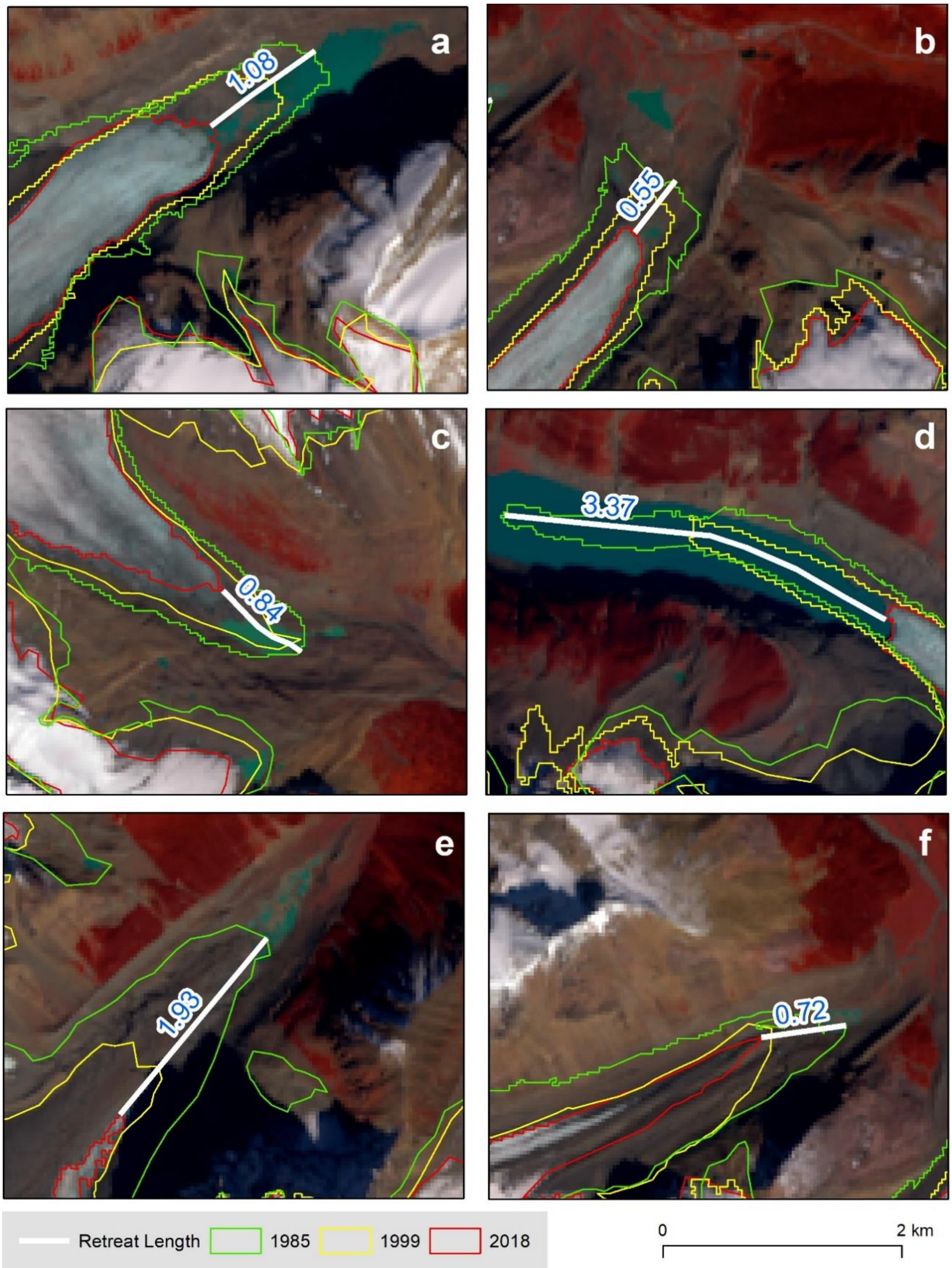

Figure 2. Length of retreat in six major glaciers in Columbia Icefield. Glacier names: (**a**) = Saskatchewan, (**b**) = Athabasca, (**c**) = Castleguard, (**d**) = Columbia, (**e**) = Stutfield, (**f**) = Dome.

Total area change from 1985 to 2018 (Table 3) was 42.56 km^2 for the entire Icefield. The Columbia Glacier lost the largest absolute area of 5.62 km^2 at a rate of 1.02% a^{-1} between 1985 and 2018 while G242711E52106N (G13) lost the smallest relative area (0.1 km^2) at a rate of 0.27% a^{-1} between 1985 and 2005. The least absolute and relative area loss changes were recorded by the G242711E52106N (G13) and G242808E52190N (G8) glaciers, respectively, during the study period.

Table 2. Glacier retreat of the Athabasca, Castleguard, Dome, Saskatchewan, Columbia, and Stutfield Glaciers between 1985 and 2018.

Glacier	Glacier_ID	1985–1999	1999–2018	1985–2018	Rate
		L(km)	L(km)	L(km)	L (km a^{-1})
Dome	G4	0.64	0.09	0.72	0.02
Stutfield	G2	1.49	0.43	1.93	0.06
Athabasca	G5	0.21	0.35	0.55	0.02
Columbia	G18	1.59	1.78	3.37	0.1
Castleguard	G14	0.11	0.76	0.84	0.03
Saskatchewan	G10	0.48	0.60	1.08	0.03
Mean		0.17	0.68	1.42	0.04

Table 3. Glacier area change between 1985 and 2018.

			Area			Area Change				Annual Rate
Glacier Id	Glacier	Watershed	1985	1999	2018	1985–1999	1999–2018	1985–2018	1985–2018	
	Name		km^2	km^2	km^2	km^2	km^2	km^2	(%)	(%)
G242618E52257N		Athabasca	1.2	0.8	0.6	−0.4	−0.1	−0.6	−49.4	−2.9
G242636E52211N	Stutfield	Athabasca	22.2	19.6	17	−2.5	−2.6	−5.1	−23.1	−1.4
G242667E52233N		Athabasca	2.6	1.9	1.7	−0.6	−0.2	−0.9	−34.1	−2
G242700E52191N	Dome	Athabasca	9.1	7.9	6.7	−1.3	−1.1	−2.4	-26.4	−1.6
G242719E52168N	Athabasca	Athabasca	19	17.4	16.7	−1.6	−0.8	−2.3	−12.4	−0.7
G242808E52190N		Athabasca	1.2	1.1	0.8	−0.1	−0.3	−0.4	−35.1	−2.1
G242528E52148N	Manitoba	Athabasca	5.8	4	3.1	−1.8	−0.9	−2.7	−46.5	−2.7
G242507E52151N		Athabasca	0.4	0.6	0.2	0.2	−0.4	−0.2	−56.8	−3.3
G242484E52165N		Athabasca	3.4	3.1	2	−0.2	−1.2	−1.4	−40.7	−2.4
G242588E52208N		Athabasca	6.2	6.5	5.4	0.2	−1.1	−0.8	−13	−0.8
G242556E52214N		Athabasca	3.2	2.2	0.6	−1	−1.6	−2.6	−82.6	−4.9
G242571E52227N		Athabasca	7.5	6	5.4	−1.4	−0.6	−2.1	−27.5	−1.6
G242604E52252N		Athabasca	2	2.7	2.3	0.7	−0.3	0.4	17.7	1
G242790E52191N	Little Athabasca	Columbia	2.7	2.3	2.2	−0.4	−0.1	−0.5	−18.7	−1.1
G242690E52094N		Columbia	21.6	20.8	19.5	−0.8	−1.3	−2.1	−9.7	−0.6
G242614E52109N		Columbia	11.5	11.1	10.5	−0.4	−0.5	−1	−8.4	−0.5
G242573E52119N		Columbia	6.8	6.4	6.4	−0.4	0	−0.4	−5.6	−0.3
G242657E52180N	Columbia	Columbia	32.4	30.8	26.8	−1.6	−4	−5.6	−17.4	−1
G242808E52190N		Saskatchewan	0.9	0.2	0	−0.7	−0.2	−0.9	−100	−5.9
G242821E52181N	Hilda	Saskatchewan	2.4	0.9	0.4	−1.5	−0.5	−2	−83.2	−4.9
G242731E52135N	Saskatchewan	Saskatchewan	42.7	39.4	37.3	−3.3	−2	−5.4	−12.6	−0.7
G242766E52115N	Castleguard I	Saskatchewan	2.3	2.1	2	−0.1	−0.1	−0.3	−11.5	−0.7
G242757E52101N	Castleguard II	Saskatchewan	1.5	1	0.3	−0.4	−0.7	−1.1	−76.6	−4.5
G242711E52106N	Castleguard III	Saskatchewan	1.5	1.8	1.5	0.3	−0.3	−0.1	−4.6	−0.3
G242711E52106N	Castleguard IV	Saskatchewan	17.3	17	15.3	−0.3	−1.7	−2	−11.5	−0.7
			9.1	8.3	7.4	−0.8	−0.9	−1.7	−31.6	−1.9
			227.4	207.6	184.8	−19.8	−22.8	−42.6	−18.7	−1.1

An overlay of the 1985, 1999, and 2018 glacier boundaries, showed a loss in extent of ice in all three watersheds (Athabasca, Columbia and Saskatchewan). For the Athabasca watershed, total ice area loss was 21.26 km^2, which was the largest among the three. This is partly due to the watershed hosting most of the glaciers as compared to the other two. The Columbia and Saskatchewan watersheds lost an area of 9.5 km^2 and 11.7 km^2 of their ice area. The overall mean glacier area change was 1.70 km^2 at a rate of 1.87% a^{-1} during 1985–2018. The mean area changes for the entire Icefield increased from 0.79 km^2 between 1985 and 1999 to 1.70 km^2 between 1999 and 2018. The estimated error in area change measurements is ± 11.84 km^2.

For further analysis, the glaciers were divided into classes according to their sizes based on the 1985 image: <1 km^2, 1–5 km^2, 5–10 km^2, 10–15 km^2, 15–20 km^2, and >20 km^2. Glaciers between 1.0 and 5.0 km^2 had the largest composite of glaciers per class (Table 4). It was observed that larger glaciers (>20 km^2) tend to have the greatest absolute area loss (-18.23 km^2; -15.3%), at a rate of -0.5%a^{-1}, while the smaller glacier classes (<1) experience the opposing trend of the greatest relative area loss (–86.18%; 1.17 km^2) at a rate of −2.6% for the entire study period (i.e., 1985–2018). Mean glacier change was seen in all class sizes from 1985–1999 and 1999–2018 as shown in Table 4. Based on evidence from previous studies of the area, it was observed that there was a greater number of smaller glaciers in the area during the study period than there was before 1985. This can be attributed to the weakening and disintegration of larger glaciers into smaller portions and is evidence of glacier shrinkage.

Table 4. Changes in class sizes of the glaciers between 1985 and 2018.

Class (km^2)	Count	Mean Area km^2	1999–1985 Change km^2	1999–1985 Change (%)	2018–1999 Change km^2	2018–1999 Change (%)	1985–2018 Change km^2	1985–2018 Change (%)	Annual Rate km^2	Annual Rate (%)
<1	2	0.7	−0.6	−40.9	−0.6	−76.6	−1.2	−86.2	0.0	−2.6
1.0–5.0	11	2.2	−3.9	−16.5	−5.5	−27.8	−9.5	−39.8	−0.3	−1.2
5.1–10	5	7.1	−4.7	−13.2	−3.7	−12.0	−8.4	−23.6	−0.3	−0.7
10.0–15.0	1	11.5	−0.4	−3.9	−0.5	−4.7	−1.0	−8.4	0.0	−0.3
15.0–20.0	2	18.2	−1.9	−5.3	−.4	−7.1	−4.3	−12.0	−0.1	−0.4
>20	4	29.7	−8.3	−7.0	−9.9	−9.0	−18.2	−15.3	−0.6	−0.5
Mean			−3.3	−8.7	−3.8	−11.0	−1.7	−30.9	−0.1	−1.8
Total	25		−19.8	−8.7	−22.8	−11.0	−42.6	−18.7	−1.3	−1.1

6. Discussion and Conclusions

The pattern observed in this study is one of general ice loss in the Columbia Icefield. All glaciers retreated and decreased in area cover over the study period. The termini of the six major glaciers—Athabasca, Columbia, Saskatchewan, Stutfield, Dome, and Castleguard—decreased in area by an average of 1.3 km^2 while the total area loss of the entire Icefield was 42.56 km^2 at a rate of 1.29 km^2 a^{-1} during the study period. Between 1985 and 2018, the mean retreat of the six major glaciers was 1.43 km at a rate of 0.04 km a^{-1}.

The rate of glacier area changes in this study (0.57% a^{-1}) is comparable to the findings of Bolch et al. [12] in their study of Western Canada. Their study revealed an area loss rate of 0.6 ± 0.19% a^{-1} for the Southern Canadian Rockies, which includes the Columbia Icefield, between 1985 and 2005. From this rate, glacier change may be very subtle; hence, it may take a longer period of glacier monitoring to detect significant changes. However, a perfect agreement with other studies is not to be expected due to differences in the study periods and the extent of spatial coverage. In this study, the highest absolute glacier retreat was recorded for the Columbia Glacier (1.94 ± 0.05 km). This is similar to the results of Tennant and Menounos [15], who, for the same glacier, found the highest retreat of 3.7 ± 0.03 km between 1919 and 2006. The Saskatchewan Glacier had the largest absolute area loss, which is also in agreement with the findings of Tennant and Menounos [15].

Glacier retreat have led to the formation of small water bodies in Athabasca, Columbia, and Saskatchewan watersheds in the study area. Formation of water bodies was also observed in other mountain glaciers in Western Canada [22,24]. Although ice loss patterns have been observed and reported in studies between the mid-1990s and 2000, the area, like other glaciers worldwide, is characterized by variability in glacier parameters, and it is mostly dependent on climate change, among other factors. While the average glacier retreat was 1.43 km within the study period, there were irregular glacier landscape features for every year in the study period. For instance, Baumann [25], measured glacier changes in the Columbia Glacier every year between 1985 and 2010. That study showed that the glacier advanced in some years while in other years (1998, 1999, and 2008), it did not change at all. This could be the case of the other major glaciers in the Icefield due to altitude and changes in snow precipitation over the years.

As seen in some previous studies [15,24], when glacier changes were evaluated according to their class values, smaller-sized glaciers experienced higher relative area loss rates compared to larger-sized glaciers, that had the largest absolute retreat. This is because the larger glaciers have the greatest ice cover to lose. However, the smaller glaciers, which also are usually the detached glaciers, recorded lower relative area loss than the larger glacier bodies, which are avalanche-fed. For each class between 1985–2018, it was observed that the mean rate of area lost for each class-size increased over the subsequent time period (1985–1999 and 1999–2018). The number of individual glaciers within the Columbia Icefield increased compared to years prior to 1985, mainly because a few the larger glaciers disintegrated into smaller portions as they became weak and unstable.

On error analysis, although we were able to provide rough estimates, we do acknowledge that error estimation in glacial studies is still very challenging, and there may be some error sources associated with the study area. A thorough review of glaciology literature reveals that the glaciological community has not emphatically reached a consensus [26] on the subject concerning the best method for error analysis. Thus, a few studies fully quantify errors associated with their mapping. For instance, in this study, we decided to use the GIS buffer method for error analysis, which presented two different measurement possibilities. The first uses 1 pixel size (30 m) [20,26] as the buffer distance. The second uses error length [6,15] as the distance of the buffer, which usually combines one-half of the resolution and the RMSE of the scene. The latter was employed because we wanted to maintain consistency with previous studies of the area.

Since the Columbia Icefield is in a mountainous region, it is important to consider errors that can be introduced by topographic illumination. Our overall confidence in mapping the area is high in regions of clean ice but is slightly less in regions covered in debris, which posed as a major error source due to lack of field data. The use of Google Maps and Bing images helped, but we were unable to justify the clear extent in the debris-covered terminus. Fortunately, the debris cover was relatively low compared to the clean ice areas; thus, we are highly confident in our area delineation and error estimates. The use of the band ratio helped to illuminate internal rocks, which were primarily in cast shadows. Going forward, field data or more improved methods for clearly mapping debris cover may be necessary for proper mapping.

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