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Area change of glaciers in the Canadian Rocky Mountains, 1919 to 2006

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Abstract

We used Interprovincial Boundary Commission Survey (IBCS) maps of the Alberta–British Columbia (BC) border (1903–1924), BC Terrain Resource Information Management (TRIM) data (1982–1987), and Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) imagery (2000–2002 and 2006) to document planimetric changes in glacier cover in the Central and Southern Canadian Rocky Mountains between 1919 and 2006. Total glacierized area decreased by 590 ± 100 km^2 (40 ± 7 %), with 17 of 523 glaciers disappearing and 124 glaciers fragmenting into multiple ice masses. Fourteen of the glaciers that disappeared were less than 0.5 km^2, and glaciers smaller than 1.0 km^2 experienced the greatest relative area loss (64 ± 17 %). Variation in area loss increased with small glaciers, suggesting local topographic setting controls the response of these glaciers to climate change. Absolute area loss negatively correlates with slope and minimum elevation, and relative area change negatively correlates with mean and median elevations. Similar average rates of area change were observed for the periods 1919–1985 and 1985–2001, at −6.3 ± 0.9 km^2 yr^{-1} (−0.4 ± 0.1 % yr^{-1}) and −5.0 ± 0.5 km^2 yr^{-1} (−0.3 ± 0.1 % yr^{-1}), respectively. The rate of area loss significantly increased for the period 2001–2006, −19.3 ± 2.4 km^2 yr^{-1} (−1.3 ± 0.2 % yr^{-1}), with continued high minimum and accumulation season temperature anomalies and variable precipitation anomalies.

1 Introduction

Glaciers adjust their form in response to climate. Mass balance provides the most direct link with climate, because it is a response to meteorological conditions on a seasonal or annual time scale (Dyurgerov and Bahr, 1999; Pelto, 2006). However, only a few such records exceed 20 yr, and they are spatially limited due to the time, expense, and access needed to collect the data (Dyurgerov and Meier, 2000; Andreassen et al., 2002; Berthier et al., 2004; Barry, 2006). Changes in glacier area are an indirect link with climate because they are a delayed response to long-term climate change (Dyurgerov and Bahr, 1999; Dyurgerov and Meier, 2000; Barry, 2006; Pelto, 2006). Area change measurements can be less labour intensive and cover more area than mass balance measurements, but long records are still needed to investigate the relation between glaciers and climate.

Glaciers in the Canadian Rocky Mountains constitute an important freshwater resource. Glacier runoff flows into four major watersheds, the Mackenzie, Nelson, Fraser, and Columbia River basins and drains into the Arctic, Atlantic, and Pacific oceans. The contribution of meltwater to total discharge may be low, but glacier runoff supplements the summer flow and regulates stream temperature, which is important for aquatic ecosystems, irrigation, industry, hydro power and human consumption (Henoch, 1971; Barry, 2006; Granshaw and Fountain, 2006; Stahl and Moore, 2006; Moore et al., 2009; Marshall et al., 2011). As glaciers retreat, there is an initial increase in runoff followed by a decline as volume is lost; this condition is likely affecting glaciers in the Canadian Rocky Mountains (Moore et al., 2009; Marshall et al., 2011).

Bolch et al. (2010) completed a glacier inventory of Western Canadian glaciers for the period 1985–2005. Although this inventory encompasses all of the Canadian Rocky Mountains, it is temporally limited. In this region, early 20th century glacier measurements tend to be limited to terminus positions of a few easily accessed glaciers (Field, 1948; Meek, 1948; Heusser, 1956). During the Interprovincial Boundary Commission Survey (IBCS) of the Alberta–British Columbia (BC) border between 1903 and 1924, maps containing glacier extents and contours were created through photo-topographic methods using oblique terrestrial photographs taken from mountain ridges (Interprovincial Boundary Commission, 1917; Wheeler, 1920). These maps, once properly corrected for topographic distortion and systematic bias, provide an important dataset to extend the glacier inventory of the Canadian Rocky Mountains back in time.

The objectives of this study are to: (a) calculate changes in glacier cover from 1919 to 2006 for the Central and Southern Canadian Rocky Mountains; (b) relate changes in area to glacier properties such as slope, aspect, and mean, median, and minimum elevations, and; (c) compare changes in glacier cover to changes in climate.

2 Study area

This study focuses on glaciers in the Central and Southern Canadian Rocky Mountains that were mapped during the 1903–1924 IBCS of the Alberta–BC border. The Central and Southern Canadian Rocky Mountains trend north-northwest and form the Continental Divide between Alberta and BC (Fig. 1). Differential weathering and erosion of uplifted, resistant Paleozoic carbonates and weaker Mesozoic sandstones and shales, and recurrent alpine and continental glaciations, have formed the high relief (1000 to 4000 m above sea level, a.s.l.) of the region (Heusser, 1956; Osborn et al., 2006). The two highest peaks in the Canadian Rocky Mountains are Mt. Robson (3954 m a.s.l.) and Mt. Columbia (3747 m a.s.l.).

This region is comprised of alpine and subalpine ecosystems (Heusser, 1956; BC Ministry of Forests, 1998). Cold temperatures, long winters, short summers, and high amounts of precipitation, with abundant snowfall, are typical of these ecosystems (BC Ministry of Forests, 1998). Mean annual temperature and total annual precipitation are −2.7 °C and 1299 mm, respectively (Fig. 2) (Wang et al., 2012). Maritime polar air masses dominate the Canadian Rocky Mountains west of the Continental Divide; cyclonic storms cross the region from the North Pacific between September and June (Heusser, 1956; Henoch, 1971; Hauer et al., 1997). East of the divide, continental polar air masses dominate, particularly during winter (Heusser, 1956; Hauer et al., 1997).

In 2006, total glacier cover of the study area was ca. 900 km^2 (Bolch et al., 2010). Glacier types include valley, cirque, icefield outlet, avalanche-fed, debris-covered, land-terminating, and lake-terminating glaciers (Heusser, 1956; Denton, 1975; Schiefer et al., 2008; Bolch et al., 2010). Glaciers range in size up to 40 km^2, have a median elevation of 2500 m a.s.l., and predominantly face north to northeast (Schiefer et al., 2008). The main icefields from north to south are Resthaven, Reef, Hooker, Chaba, Clemenceau, Columbia (the largest), Lyell, Mons, Freshfield, Wapta, and Waputik.

3 Data and methods

3.1 Interprovincial Boundary Commission Survey maps

The IBCS maps consist of 54 maps at a scale of 1:62 500 with a contour interval of 100 feet, produced from 1903 to 1924. Scanned digital copies of the maps were obtained from Library and Archives Canada. Of the 54 maps, 30 contained glaciers and were used in this analysis.

We rectified the IBCS maps in PCI Geomatica OrthoEngine v.10.2 using a 5th order polynomial transformation model that adjusts the positions of mapped features based on ground control points (GCPs). We collected 25–40 GCPs per map (Fig. 3) from previously rectified Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) imagery, and a shaded relief model (hillshading) derived from the BC Terrain Resource Information Management (TRIM) digital elevation model (DEM; Table 1). Mountain peaks and ridges were the main source of GCPs as they were easy to identify on the maps and represent stable, vegetation-free areas. As the polynomial transformation did not use elevation data, we focused on spatially distributed GCPs rather than an altitudinal distribution. However, GCPs from the valleys were needed to provide control for glacier termini and map edges, so we used the centers of small lakes, as shorelines may have changed over ca. 80 yr. The average root mean square errors (RMSE) in the easting and northing were 12.2 and 11.5 m, respectively, with a minimum value of 2.3 m and a maximum value of 24.9 m. We also visually checked the features on the maps against the BC TRIM hillshading and Landsat imagery.

3.2 Data collection

We digitized glacier extents and contours from the rectified IBCS maps. There are no glacier boundary lines on the maps, although the contour lines of the glaciers are blue, rather than brown. We therefore digitized around the blue contours to delineate glacier extents (Fig. 4). Where maps overlapped, we digitized glacier extents and contours from the map that exhibited the least offset from the Landsat imagery. We also generated a DEM from the contours to extract glacier properties from these historic maps.

We compared the IBCS glacier extents with glacier polygons in the Landsat-based glacier inventory of Western Canada (Bolch et al., 2010), also available from the Global Land Ice Measurements from Space (GLIMS) program (http://www.glims.org). Extents were available for the periods 1982–1987, 2000–2002, and 2006 (Table 1). All glacier extents were clipped to the IBCS map extents and separated into glacier flowsheds modified from Bolch et al. (2010). These flowsheds were based on drainage basins and, depending on a specific period, may contain one or several glaciers.

We used the median year of the glacier coverage (1919, 1985, 2001, and 2006) to define approximate acquisition dates for the glacier data as a whole, although individual area change was calculated based on the actual year for a given flowshed. For the IBCS data, where multiple maps may have been used for a given flowshed, we used the average date of the two maps.

3.3 Error analysis

Mapping and printing errors (21 % of flowsheds) were evident in the IBCS maps (Fig. 5a–c). In some cases, glacier contours were shifted in relation to the land contours, making the location of the glacier margin difficult to determine. We placed the glacier margin halfway between the shift of the land and glacier contours. We found one instance of a missing terminus of a large glacier (Fig. 5b), where the cartographer estimated the feature due to incomplete photographic coverage (Wheeler, 1988). In some cases, glaciers extended beyond the limit of the map sheet (6 %). These situations pose a problem in calculating area change for a given flowshed, and so we removed them from the analysis.

When comparing IBCS glacier extents with those from 1985, 2001, and 2006, we noticed missing glaciers in one or more of the glacier inventory extents. In these cases, we manually digitized the extents from the original Landsat imagery that had been used to create the glacier inventory (see Bolch et al., 2010, for list of Landsat imagery). We also assembled and edited a ca. 2001 glacier extent for the Central Canadian Rocky Mountains, as no finished inventory for this epoch existed in the data originally assembled by Bolch et al. (2010) (Fig. 5d). We inspected each glacier extent overlain on the imagery and manually modified the extents where we noticed mismapped glaciers. For the 1985 extents, we did not have complete Landsat imagery coverage to check the BC TRIM data, so any observed errors (4 %) or missing glaciers (8 %) could not be corrected (Fig. 5e). Some glacier extents (5 %) could not be added or corrected due to shadows and cloud cover (Fig. 5f).

To reduce the potential bias imposed by these mapping errors, we did not compare planimetric change of flowsheds where problematic glaciers exist and removed them before area change analysis was conducted. Of the original 937 flowsheds, 414 (44 %) were removed, leaving 523 flowsheds for analysis.

The error terms for glacier extents from the glacier inventory of Western Canada are 3–4 % (Bolch et al., 2010). However, we had to modify the extents for snow cover, shadows, and missing glaciers, so we calculated new error terms for all extents using a buffer method similar to Granshaw and Fountain (2006) and Bolch et al. (2010). We calculated an error term for the 1919 extents using a buffer equal to the estimated horizontal error (30 m), incorporating the RMSE of the map rectification (16 m), a digitizing error equal to half the width of a contour line (7.5 m), and half the mean offset between overlapping maps (25 m). For the glacier inventory extents, we used a buffer equal to half the resolution of the data (Table 1). As the 1985 extents were from BC TRIM data and Landsat imagery, we used a buffer equal to half of the combined resolution (11 m). Between each period, we calculated a RMSE term using the error estimates from the two years that make up a period. Calculated error terms are listed in Table 2 and range from 7.8 to 18.8 % for the individual years and 9.8 to 16.6 % for the periods.

3.4 Glacier change analysis

For each flowshed, we calculated the glacierized area and number of ice masses. We determined the mean, median, and minimum elevations of ice within each flowshed, and derived the mean slope and aspect from the DEMs (Table 1). Using the Solar Radiation tool (algorithms developed by Fu and Rich, 2002) in ArcGIS v. 9.3, we produced a surface of clear sky incoming solar radiation (insolation, $\mathrm{W\,h\,m^{-2}}$) from the BC TRIM/Alberta DEM. We calculated absolute ($\mathrm{km^2}$) and relative (%) area change and rates between successive years, and compared them with the properties mentioned above.

3.5 Climate data

We obtained monthly minimum, mean, and maximum temperatures and monthly total precipitation from 1901 to 2006 at the centre of each glacier, based on latitude, longitude, and elevation, from the ClimateWNA v.4.62 program (http://www.genetics.forestry.ubc.ca/cfcg/ClimateWNA/ClimateWNA.html). This program extracts climate data at specific locations from downscaled PRISM and historical data using anomalies (Wang et al., 2012). Anomaly surfaces are derived from interpolated historical data created by Mitchell and Jones (2005) and a baseline reference grid (2.5 arc min) of monthly climate data for the 1961–1990 normal period generated by PRISM (Daly et al., 2002). Bilinear interpolation and lapse-rate elevation adjustments are used to integrate the historical anomaly surfaces and the baseline grid and downscale the climate data at a specific location (Mbogga et al., 2009; Wang et al., 2012). More detailed information on the methodology behind the datasets can be found in Wang et al. (2012).

We calculated total annual precipitation based on the water year, October to September, as well as total ablation (May to September) and accumulation (October to April) season precipitation. Total precipitation was used because snow is common throughout the year at high elevation. We determined minimum, mean, and maximum annual temperature, in addition to ablation and accumulation season temperature.

We compared area change with annual and seasonal total precipitation and minimum, mean, and maximum temperature, by flowshed. Also, we averaged the temperature and precipitation data over all of the flowsheds to produce one value for the region for each year. We derived temperature and precipitation anomalies from the 1919–2006 annual and seasonal means and grouped them into three periods: 1919–1985, 1985–2001, and 2001–2006. We chose these three periods to match the periods of area changes and rates.

4 Results

4.1 Glacier properties

In 1919, the Canadian Rocky Mountains contained 569 mapped ice masses in 523 flowsheds inventoried by this study, with a total area of 1470 ± 280 km^2. Each flowshed represents total ice draining an area, which may include multiple ice masses (e.g. an avalanche-fed glacier with a separate accumulation area or disconnected tributary glaciers). For the 1919 data, however, the glacierized area within a flowshed is considered to represent one glacier.

Glacier areas ranged in size from 0.06 ± 0.01 km^2 to 50 ± 9 km^2 (Freshfield Glacier); the mean glacier area was 2.9 ± 0.5 km^2. We separated glaciers into six size classes based on the 1919 areas: 0.05–0.1 km^2, 0.1–0.5 km^2, 0.5–1.0 km^2, 1.0–5.0 km^2, 5.0–10.0 km^2, and >10.0 km^2. The 1.0–5.0 km^2 class contained the greatest number of glaciers (37 % of the total). Glaciers smaller than 1.0 km^2 contained 49 %; the >10.0 km^2 class had the greatest area (41 %; Fig. 6). Glaciers existed between 1410 and 3860 m a.s.l. and had a mean elevation range of 620 m. Both mean and median elevations of the glaciers were 2470 m a.s.l., and mean slope was 19°, with a range from 6° to 46°. The majority of glaciers faced north and northeast (45 %); few glaciers had a southwest aspect (5 %).

By 2006, glacierized area in the Canadian Rocky Mountains had decreased to $880 \pm 120\,\mathrm{km}^2$, a loss of $590 \pm 100\,\mathrm{km}^2$ since 1919. The number of ice masses increased to 724 due to the disintegration of 124 glaciers (Fig. 7), although, 13 ice masses disappeared from flowsheds still containing glaciers in 2006, and 17 glaciers disappeared completely. Fourteen of the 17 glaciers that disappeared had been smaller than $0.5\,\mathrm{km}^2$.

Since 1919, mean glacierized area per flowshed has decreased to $1.7 \pm 0.2\,\mathrm{km}^2$. There also has been a shift in the number of glaciers by size class to smaller glaciers (Fig. 6). In 2006 the $0.1–0.5\,\mathrm{km}^2$ class contained the greatest percentage (45 %) of glaciers. Elevation data were not available for 2006, so elevation properties, slope, and aspect, are based on data from 1999. Glaciers occurred at elevations between 1570 and 3660 m a.s.l., a decrease in the elevation range since 1919. However, the decrease in maximum elevation may be due to errors in the uncorrected 1919 DEM. Mean and median elevations increased to 2530 m a.s.l., mean slope increased to 21°, and the distribution of glaciers by aspect remained unchanged.

4.2 Area change

From 1919 to 2006, glaciers lost a total area of $590 \pm 100\,\mathrm{km}^2$ ($40 \pm 7\,\%$) at a rate of $-6.8 \pm 1.1\,\mathrm{km}^2\,\mathrm{yr}^{-1}$ ($-0.5 \pm 0.1\,\%\,\mathrm{yr}^{-1}$). The $1.0–5.0\,\mathrm{km}^2$ class had the greatest absolute area loss ($242 \pm 30\,\mathrm{km}^2$; Fig. 8). Relative area loss was greatest for the $0.5–1.0\,\mathrm{km}^2$ class ($67.8 \pm 12\,\%$); glaciers smaller than $1.0\,\mathrm{km}^2$ lost on average $64 \pm 17\,\%$ of their area (Fig. 8). Glaciers in the $0.05–0.1\,\mathrm{km}^2$ class decreased the least in total area, whereas large glaciers ($>10.0\,\mathrm{km}^2$) lost the smallest area when expressed as a percentage.

The median absolute (relative) rates of area change for the periods 1919–1985 and 1985–2001 are similar, with values of $-0.0065 \pm 0.0009\,\mathrm{km}^2\,\mathrm{yr}^{-1}$ ($-0.50 \pm 0.07\,\%\,\mathrm{yr}^{-1}$) and $-0.0047 \pm 0.0005\,\mathrm{km}^2\,\mathrm{yr}^{-1}$ ($-0.45 \pm 0.04\,\%\,\mathrm{yr}^{-1}$), respectively (Fig. 9). Rates of area change for the period 2001–2006 are significantly higher, with values of $-0.0200 \pm 0.0025\,\text{km}^2\,\text{yr}^{-1}$ ($-1.67 \pm 0.21\,\%\,\text{yr}^{-1}$). Total absolute (relative) rates of area change are $-6.3 \pm 0.9\,\text{km}^2\,\text{yr}^{-1}$ ($-0.43 \pm 0.06\,\%\,\text{yr}^{-1}$), $-5.0 \pm 0.5\,\text{km}^2\,\text{yr}^{-1}$ ($-0.34 \pm 0.03\,\%\,\text{yr}^{-1}$), and $-19.3 \pm 2.4\,\text{km}^2\,\text{yr}^{-1}$ ($-1.31 \pm 0.16\,\%\,\text{yr}^{-1}$) for the periods 1919–1985, 1985–2001, and 2001–2006, respectively. These patterns in the absolute and relative rates of area change are consistent across the different glacier size classes.

As expected, a strong relation ($r^2 = 0.87$, $p < 2.2e^{-16}$) exists between areas of glaciers in 1919 and 2006 (Fig. 7):

$$A_{1919} = 10^{0.80\log(A_{2006})+0.34} \tag{1}$$

where A_{1919} and A_{2006} denote the areas of a glacier in 1919 and 2006, respectively. Equation (1) can thus be used to estimate glacier extents in regions of the Canadian Rocky Mountains not covered by the IBCS. Using the 2006 area of each glacier in the Central and Southern Canadian Rocky Mountains in the glacier inventory created by Bolch et al. (2010), we calculated a total glacierized area of 3150 km^2 (1250–7960 km^2, 95 % prediction interval) for 1919. The total glacierized area of this region in 2006 was 1770 km^2, resulting in an area change of –1380 km^2 (–44 %) from 1919 to 2006.

Most variability in Fig. 7 is associated with glaciers with areas between 0.5 and 5 km^2. We correlated the model residuals with possible explanatory factors, such as elevation, slope, aspect, insolation, and climate. Mean slope had the highest correlation, with an r value of –0.39 ($p < 0.01$), followed by mean and median elevations ($r = -0.19$, $p < 0.01$), maximum ablation season temperature ($r = -0.18$, $p < 0.01$), and mean ablation season temperature ($r = -0.17$, $p < 0.01$). There are no significant correlations between latitude, longitude, or insolation and residuals, and no observable trends between residuals and aspect. Because mean slope ($\bar{s}$) has a moderate correlation with the model residuals, we included it in the model (Eq. 2), which improved the relation ($r^2 = 0.90$, $p < 2.2e^{-16}$) and reduced the residual standard error from 0.20 to 0.18.

$$A_{1919} = 10^{0.73\,\log(A_{2006})+0.02\bar{s}+0.65} \tag{2}$$

The resulting glacierized area in 1919 using Eq. (2) was 2970 km^2 (1290–6820 km^2, 95 % prediction interval), with a total change in area of −1200 km^2 (−42 %), between 1919 and 2006.

4.3 Area change with properties

We compared absolute and relative glacier area changes in the Canadian Rocky Mountains to glacier attributes such as minimum, mean, and median elevations, surface slope, latitude, longitude, and insolation (Table 3) using Pearson's correlation. Throughout all periods, absolute area changes moderately correlate with minimum elevation (mean $r = 0.43$, $p < 0.01$) and mean slope (mean $r = 0.40$, $p < 0.01$), whereas relative area changes correlate with mean elevation (mean $r = 0.18$, $p < 0.01$), median elevation (mean $r = 0.21$, $p < 0.01$), and minimum elevation (mean $r = -0.16$, $p < 0.01$). There are weak significant correlations between both types of area change and latitude, longitude, and insolation, but they differ in strength between the periods. Absolute area changes are greatest for glaciers with north and northwest aspects; these aspects support the largest glacier area. There is no observable relation between relative area change and aspect. The correlations among rates of area change and the glacier properties mirror those between area change and glacier properties.

4.4 Climate

Temperature anomalies are ca. −0.1 °C from the 1919–2006 mean for the period 1919–1985, with accumulation season (ca. −0.2 °C) and all minimum temperature anomalies (ca. −0.3 °C) slightly below average (Fig. 10). Since 1985, all minimum temperature anomalies are ca. 0.7 °C above the 1919–2006 average. Maximum ablation season temperature anomalies are ca. −0.4 °C below average, but accumulation season temperature anomalies are ca. 0.4 °C above average for the period 1985–2001. In the recent period, 2001–2006, all temperature anomalies are 0.5 °C above average except for ablation season maximum temperature anomalies.

Precipitation anomalies are negative (ca. −20 mm) for the period 1919–1985 and positive (ca. 25 mm) for the period 1985–2001. The period 2001–2006 had the most negative precipitation anomaly (ca. −68 mm) and was most variable.

We examined the spatial and temporal relations between climate and glacier change. We correlated absolute and relative area changes and rates with epoch-averaged temperature and precipitation for each flowshed (Table 3). Absolute area changes and rates were correlated with accumulation season (mean $r = -0.21$, $p < 0.01$) and annual precipitation (mean $r = -0.15$, $p < 0.05$), as well as mean and maximum accumulation season temperature (mean $r = 0.11$, $p < 0.05$). Relative area changes and rates are correlated with all temperatures (mean $r = -0.15$, $p < 0.05$) and with accumulation season precipitation (mean $r = 0.15$, $p < 0.05$).

5 Discussion

5.1 Area change

Glaciers in the Canadian Rocky Mountains, analyzed by this study, decreased 590 ± 100 km^2 (40 ± 7 %) between 1919 and 2006. The errors reflect uncertainties in the glacier extents, primarily from the IBCS maps where extents may have been incorrectly mapped due to snow cover, or estimated where photographic coverage was incomplete or the perspective was poor (Wheeler, 1988). However, shadows, debris cover, snow cover, and clouds introduce uncertainties in all years.

We compared our results to those of Bolch et al. (2010) from the Southern and Central Canadian Rocky Mountains, because we used a subset of their glacier inventory data. A perfect comparison was not expected because we modified and edited the glacier extents, but we found our area changes comparable to those of Bolch et al. (2010) within error. Between 1985 and 2005, area changes from Bolch et al. (2010) are −17.5 ± 4.1 % and −14.8 ± 4.1 % for the Central and Southern Canadian Rocky Mountains, respectively, similar to our estimate of −16.7 ± 1.9 %

for the combined region over the same period. The rates for Bolch et al. (2010), -0.47 ± 0.36 and $-1.21 \pm 0.96\,\%\,\mathrm{yr}^{-1}$, are also similar to our estimates, -0.34 ± 0.03 and $-1.31 \pm 0.16\,\%\,\mathrm{yr}^{-1}$, for the periods 1985–2000 and 2000–2005, respectively.

Direct comparisons are difficult to make with other inventories, as most values are calculated for different periods. Interpretation differences, mapping errors, and the number of glaciers may also contribute to discrepancies between inventories. Other glacier area change estimates for the Canadian Rocky Mountains range from −15 to −25 % from ca. 1950 to 2000 (Luckman and Kavanagh, 2000; DeBeer and Sharp, 2007), and −22 to −36 % from 1975 to 1998 (Demuth et al., 2008). Jiskoot et al. (2009) calculated rates of area change of −9 % per decade and −19 % per decade for the Clemenceau and Chaba icefields, respectively, from 1985 to 2001.

Glaciers in the Northern and Southern Coast Mountains of British Columbia shrank less (−8 to −10 % from 1985–2005) than those of the Canadian Rocky Mountains, primarily due to the larger sizes of glaciers and possible influence of a maritime climate (Bolch et al., 2010). Most inventories for the Northern Hemisphere determine glacier change after 1950 to the end of the 20th century, and range from 7 to 32 % area loss (Kääb et al., 2002; Paul, 2002; Granshaw and Fountain, 2006; Bolch, 2007). Two studies that report glacier area change since the early 1900s report area losses of 23 % between 1930 and 2003 for Jotunheimen, Norway (Andreassen et al., 2008), and 49 % and 35 % between 1850 and the mid-1970s for glaciers in the New Zealand and European Alps, respectively (Hoelzle et al., 2007).

In the Canadian Rocky Mountains, small glaciers ($<1.0\,\mathrm{km}^2$) lost the greatest percentage of their area. This result is consistent with those of the majority of the studies mentioned above (Kääb et al., 2002; Paul, 2002; Granshaw and Fountain, 2006; Demuth et al., 2008). Granshaw and Fountain (2006) argue that this difference is due to a high area-to-volume ratio, so for the same ablation rate, small glaciers should shrink faster. Another possible explanation is that small glaciers have a higher perimeter-to-area ratio, which makes them increasingly susceptible to radiation from the surrounding terrain (Demuth et al., 2008).

DeBeer and Sharp (2007) found that glaciers in the 1.0–5.0 km^2 class had the highest absolute area loss due to the large number of glaciers in this size class and high individual area loss, similar to our results (Fig. 8). However, they found that small glaciers ($<0.5\,\mathrm{km}^2$) experienced little or no change. The smaller glaciers tended to be located in more sheltered locations, at high elevations, or at sites with reduced insolation or inputs from avalanching or wind (DeBeer and Sharp, 2007; Demuth et al., 2008). This sheltering effect may be present in our data, because although we observed large percentages of area loss for small glaciers, the 0.5–1.0 km^2 class lost the highest percentage, not the smallest class (0.05–0.1 km^2).

Another trend apparent in our data and other studies (e.g. Kääb et al., 2002; Granshaw and Fountain, 2006; DeBeer and Sharp, 2007; Andreassen et al., 2008) is an increase in variability with smaller glacier sizes; the scatter can be greater than the differences between glacier size classes. It likely arises from non-climatic factors such as local topography, hypsometry, and glacier type (e.g. debris-covered), which may have a stronger influence on a glacier's response than regional climate (Kääb et al., 2002; Granshaw and Fountain, 2006; DeBeer and Sharp, 2007; Hoffman et al., 2007; Andreassen et al., 2008; Jiskoot et al., 2009). Correlating the residuals from Eq. (1), which represent the variance in the model of glacier area with glacier properties, showed that slope ($r = -0.39$) could be a factor in explaining the scatter. Adding slope to the model increased the r^2 value from 0.87 to 0.90 ($p < 2.2e^{-16}$).

5.2 Area change with glacier properties

Glacier size is the main property related to area change, but moderate correlations were also found between area changes and slope and mean, median, and minimum elevations. Absolute area loss increased with lower slopes and lower minimum elevations. These properties are typically associated with larger glaciers that extend down into valleys. Small temperature changes with elevation can influence large areas of the glacier due to the low slopes and may increase the area over which melting occurs.

Correlations with slope were also noted by Andreassen et al. (2008) and Jiskoot et al. (2009). Relative area loss increased with decreasing mean and median elevations. However, Bolch et al. (2010) did not find any correlation between area loss and median elevation for glaciers in Western Canada. Their data, however, included all glaciers in Alberta and BC, from different climates (i.e. maritime and continental), which may allow glaciers to exist at different elevations, obscuring any regional trends. Granshaw and Fountain (2006) noted a weak correlation with median elevation, as did Andreassen et al. (2008). North- and northeast-facing glaciers decreased the most, a finding similar to Andreassen et al. (2008), but these aspects also contain the greatest glacier area.

5.3 Area change with climate

Temperature and precipitation explain some of the spatial glacier changes in this study. Accumulation season precipitation has the highest correlation with absolute area change by flowshed, indicating the importance of precipitation, not just temperature on area loss. Annual and minimum ablation season temperatures are weakly correlated with percent glacier shrinkage, in agreement with previous work (e.g. Bitz and Battisti, 1999; Hoffman et al., 2007).

The period 1919–1985 has a highly variable climate (Fig. 10). Around the 1920s some glaciers in the Canadian Rocky Mountains were still near their Little Ice Age maximum extents (Field, 1948). From the 1920s to the 1950s, the climate was warm and dry, and glaciers retreated at high rates (Field, 1948; Heusser, 1956; Luckman and Kavanagh, 2000). For the second half of the period, the climate was cooler and wetter, resulting in slowed retreat or minor advances of many glaciers in the region (Henoch, 1971; Luckman and Kavanagh, 2000). This change in climate and subsequent glacier response was reported in other regions of Western North America (e.g. Luckman et al., 1987; Menounos et al., 2005; Menounos, 2006; Pelto, 2006; Hoffman et al., 2007), as well as in Europe (e.g. Andreassen et al., 2008).

The change in climate over the winter of 1945/1946 corresponds with a shift in the Pacific Decadal Oscillation (PDO) (Bitz and Battisti, 1999; Demuth et al., 2008). There was another shift in the PDO, in 1976/1977, which may have influenced the last decade of the period and persisted into the period 1985–2001. Unfortunately, these different climates are not captured in the area change or climate data, as aggregated here over both climate conditions from 1919 to 1985 produced low rates of area loss and temperature and precipitation anomalies near the 1919–2006 mean.

Rates of area loss for the period 1985–2001 are lower than those for the period 1919–1985, despite positive temperature anomalies (ca. 0.5 °C). Warmer temperatures and higher retreat rates during this period are mentioned in other studies (e.g. Pelto, 2006; Hoffman et al., 2007). However, the accumulation season precipitation anomalies were also positive, and the increased precipitation may have offset some area loss due to the warmer temperatures.

A contributing factor to the low rates of area loss for the period 1985–2001 may have been the snow cover in some of the 2000–2002 Landsat imagery resulting in an overestimation of glacier area (Bolch et al., 2010). Glaciers also may have downwasted more than retreated over this period. Area change is not an immediate response to a change in climate. Therefore, some glaciers may have been responding to the cooler and wetter climate of the previous period, 1919–1985.

The rate of glacier shrinkage was much higher between 2001 and 2006 than in the previous periods. A combination of positive temperature anomalies (>0.5 °C above average) and negative precipitation anomalies (ca. −68 mm) may be responsible. The high rate may also be a continued response from the warm temperatures of the 1980s and 1990s.

6 Conclusions

We used IBCS maps from 1919 and a portion of the Western Canada glacier inventory from 1985, 2001, and 2006 to determine area change of glaciers in the Central and

Southern Canadian Rocky Mountains. The main uncertainties and errors arise from data quality and availability. Errors in the IBCS maps included mapped snow patches, inconsistent extents, incorrect termini, and glaciers cut off at map boundaries. Although large errors are associated with the IBCS maps, they are a useful resource for early 20th century glacier extents and elevation, and over long periods, glacier changes are significantly larger than the errors in the maps. Other sources of error in the most recent datasets include late-lying snow, shadows, and debris cover, which hinder glacier delineation. Data covering the entire study area were only available for four years, and thus area change could only be evaluated over three periods. Averaging over the period 1919–1985 obscures short-term glacier change and climate variability. Also, the periods represent the available data for calculating area change and do not coincide with observed shifts in climate.

Area change was influenced predominately by glacier size, with large glaciers losing the most absolute area and small glaciers losing the most percentage of their area. Variability increases with smaller glaciers, suggesting local non-climatic factors modulate the response of these glaciers to climate. Although glacier properties, such as elevation and slope, correlate with area change, future research should focus on other properties related to glacier type and source of nourishment (i.e. outlet, cirque, avalanche-fed, and debris-covered glaciers). Temperature and precipitation are both important influences on area change, spatially correlating with individual glacier area change.

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Table 1. Data used to rectify the IBCS maps and to assess glacier change from 1919 to 2006.

Year (Date/Median)	Data Source (Path/Row)	Resolution/ Scale
Reference Data for GCP Collection		
1982–1987	BC TRIM + Alberta DEM hillshading	25 m
1985 (31 Jul)	Landsat 5 TM (45/23)	30 m
2001 (14 Sep)	Landsat 7 ETM+ (44/24)	30 m
2004 (18 Aug)	Landsat 5 TM (47/22)	30 m
2004 (28 Sep)	Landsat 5 TM (46/23)	30 m
2006 (18 Aug)	Landsat 5 TM (43/24–25)	30 m
2006 (19 Aug)	Landsat 5 TM (44/24)	30 m
2006 (26 Aug)	Landsat 5 TM (45/24)	30 m
Extents		
1903–1924 (1919)	IBCS	1:62 500
1982–1987 (1985) [1]	BC TRIM/Landsat 5 TM	1:20 000/30 m
2000–2002 (2001) [1]	Landsat 7 ETM+	30 m
2006 (2006) [1]	Landsat 5 TM	30 m
DEMs		
1903–1924 (1919)	IBCS contours	100 m
1982–1987 (1985) [1]	BC TRIM + Alberta mass points	25 m
1999 (1999)	SRTM	90 m

[1] For more detailed information on these data sources see Bolch et al. (2010). The extents are currently on the GLIMS website (http://www.glims.org).

Table 2. Error estimates for area (Year) and area change (Period).

Year	Error[1] (%)	Period	Error[2] (%)
1919	18.8	1919–1985	14.4
1985	7.8	1985–2001	9.8
2001	11.5	2001–2006	12.5
2006	13.3	1919–2006	16.6

[1] Mean error estimate calculated from individual glacier buffers.

[2] Mean RMSE calculated from the error estimates of the two differenced extents.

Table 3. Pearson's correlation coefficients (r values) of glacier properties and climate variables with absolute and relative area change by flowshed ($n = 506$). Significant correlations are denoted by $^{*} = p < 0.05$ and $^{**} = p < 0.01$.

	Absolute area change (rate)			Relative area change (rate)		
	1919–1985	1985–2001	2001–2006	1919–1985	1985–2001	2001–2006
Glacier Property[1]						
E_{min}	0.425** (0.446**)	0.379** (0.376**)	0.476** (0.461**)	−0.16** (−0.14**)	−0.20** (−0.20**)	−0.12** (−0.14**)
E_{mean}	−0.026 (−0.014)	−0.001 (0.003)	−0.004 (−0.027)	0.14** (0.18**)	0.17** (0.18**)	0.24** (0.20**)
E_{med}	−0.050 (−0.038)	−0.029 (−0.026)	−0.017 (−0.039)	0.16** (0.20**)	0.20** (0.21**)	0.27** (0.23**)
S_{mean}	0.478** (0.486**)	0.297** (0.297**)	0.413** (0.406**)	0.15** (0.15**)	−0.20** (−0.21**)	−0.12** (−0.12**)
Latitude	0.102* (0.079)	0.017 (−0.002)	−0.022 (0.021)	0.13** (0.06)	−0.07 (−0.11*)	−0.21**(−0.13**)
Longitude	−0.097* (−0.072)	−0.021 (−0.003)	0.024 (−0.023)	−0.13** (−0.07)	0.06 (0.10*)	0.22** (0.13**)
Insolation	−0.170** (−0.170**)	−0.061 (−0.063)	−0.098* (−0.101*)	−0.07 (−0.06)	0.14** (0.14**)	0.17** (0.15**)
Climate Variable[2]						
Annual T_{max}	0.091* (0.075)	0.081 (0.073)	0.084 (0.117**)	−0.13** (−0.17**)	−0.14** (−0.16**)	−0.20** (−0.14**)
Abl. T_{max}	0.051 (0.036)	0.058 (0.050)	0.059 (0.091*)	−0.15** (−0.19**)	−0.14** (−0.16**)	−0.19** (−0.13**)
Acc. T_{max}	0.127** (0.110*)	0.101* (0.093*)	0.105* (0.139**)	−0.10* (−0.15**)	−0.14** (−0.16**)	−0.20** (−0.14**)
Annual T_{mean}	0.083 (0.065)	0.064 (0.060)	0.079 (0.107*)	−0.13** (−0.17**)	−0.15** (−0.16**)	−0.19** (−0.14**)
Abl. T_{mean}	0.029 (0.015)	0.030 (0.028)	0.053 (0.073)	−0.17** (−0.20**)	−0.13** (−0.14**)	−0.15** (−0.11*)
Acc. T_{mean}	0.133** (0.112*)	0.095* (0.088*)	0.100* (0.135**)	−0.08 (−0.14**)	−0.16** (−0.18**)	−0.21** (−0.15**)
Annual T_{min}	0.098* (0.084)	0.101* (0.088*)	0.087 (0.124**)	−0.12** (−0.16**)	−0.12** (−0.16**)	−0.20** (−0.13**)
Abl. T_{min}	0.077 (0.062)	0.092* (0.076)	0.060 (0.106*)	−0.11* (−0.15**)	−0.14** (−0.17**)	−0.22** (−0.14**)
Acc. T_{min}	0.098* (0.086)	0.103* (0.090*)	0.089* (0.126**)	−0.13** (−0.17**)	−0.12** (−0.15**)	−0.20** (−0.13**)
Annual P	−0.178** (−0.182**)	−0.102* (−0.099*)	−0.171** (−0.175**)	0.03 (0.04)	0.16** (0.16**)	0.12** (0.09*)
Abl. P	−0.037 (−0.028)	0.030 (0.025)	0.013 (0.015)	−0.07 (−0.05)	0.04 (0.03)	0.03 (0.03)
Acc. P	−0.221** (−0.232**)	−0.168** (−0.160**)	−0.251** (−0.258**)	0.10* (0.10*)	0.19** (0.21**)	0.15** (0.10*)

[1] E_{min} is minimum elevation, E_{mean} is mean elevation, E_{med} is median elevation, and S_{mean} is mean slope.

[2] T_{max} is maximum temperature, T_{mean} is mean temperature, T_{min} is minimum temperature, and P is precipitation. Abl. is ablation season and Acc. is accumulation season.

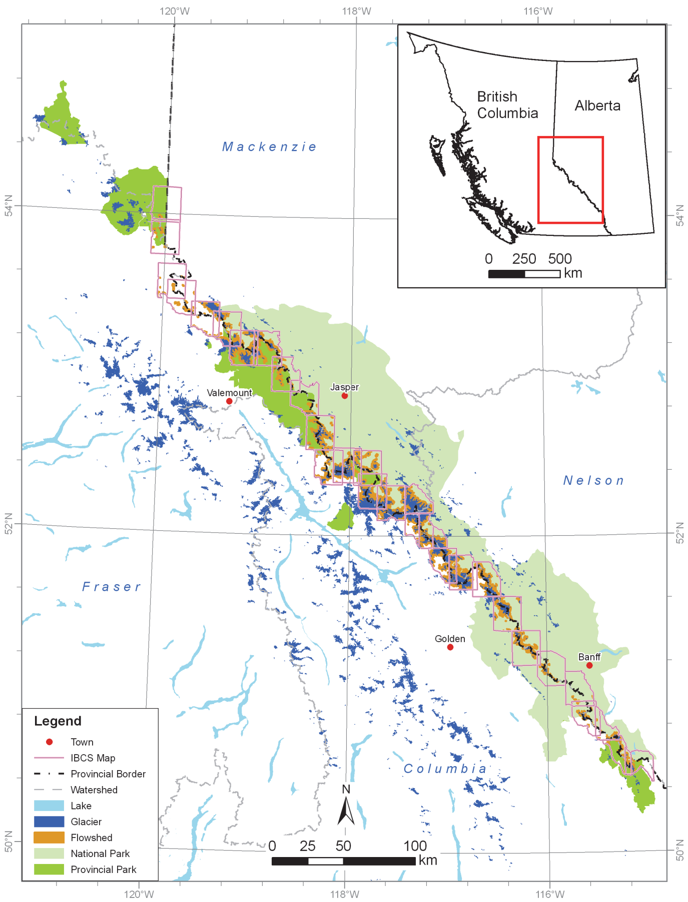

Fig. 1. Glaciers in the Central and Southern Canadian Rocky Mountains. Glaciers encompassed by the flowsheds (orange) are the focus of this study and include glaciers mapped by the Interprovincial Boundary Commission Survey between 1903 and 1924.

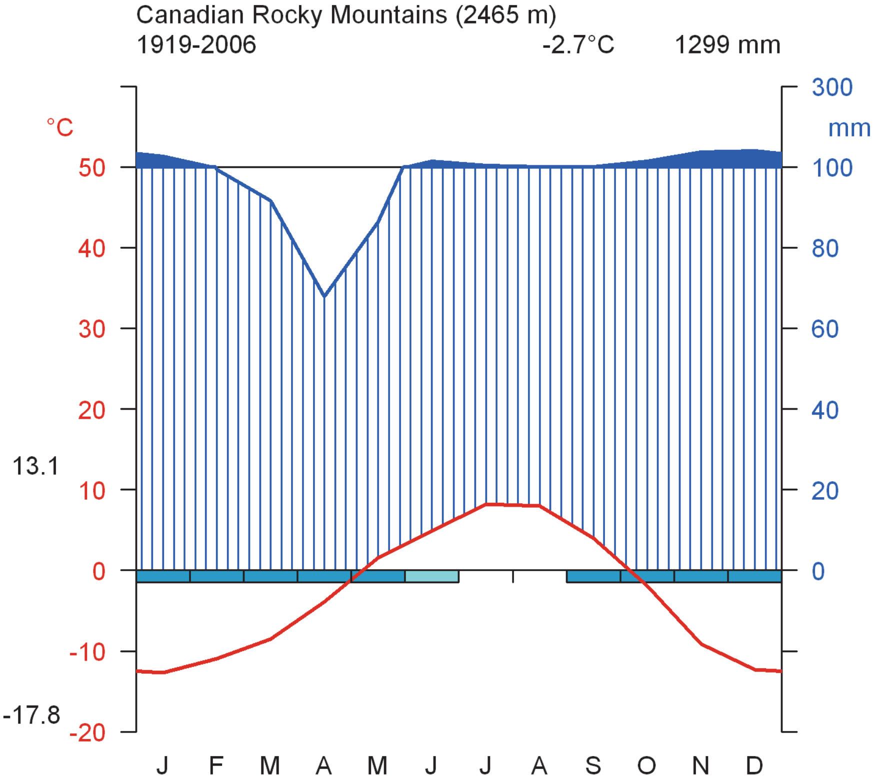

Fig. 2. Walter and Lieth climate diagram for the Central and Southern Canadian Rocky Mountains, showing monthly mean temperature (red), monthly mean precipitation (blue vertical striping), frost periods (blue boxes), and probable frost periods (cyan boxes). Precipitation greater than 100 mm is plotted at a reduced scale of 10:1. Absolute maximum and minimum temperatures are given on the left (black). Data are monthly temperature and precipitation values from ClimateWNA (Wang et al., 2012), compiled over the period 1919–2006 from the centre and mean elevation of each glacier.

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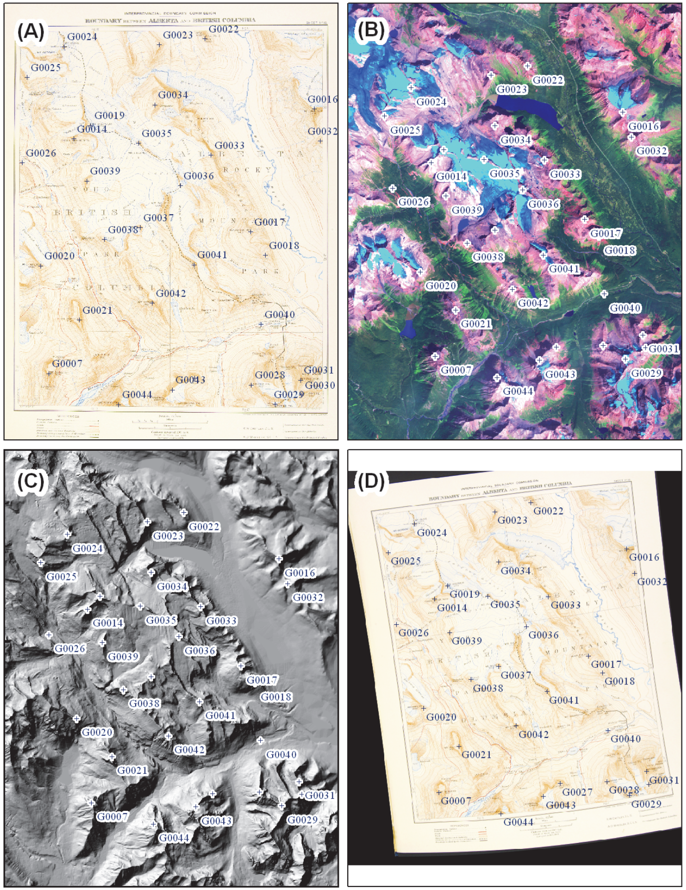

Fig. 3. (A) Example of a raw IBCS map that was rectified using 30 GCPs collected from **(B)** previously rectified Landsat imagery and **(C)** BC TRIM hillshading to produce **(D)** a rectified map from which glacier extents and contours were extracted.

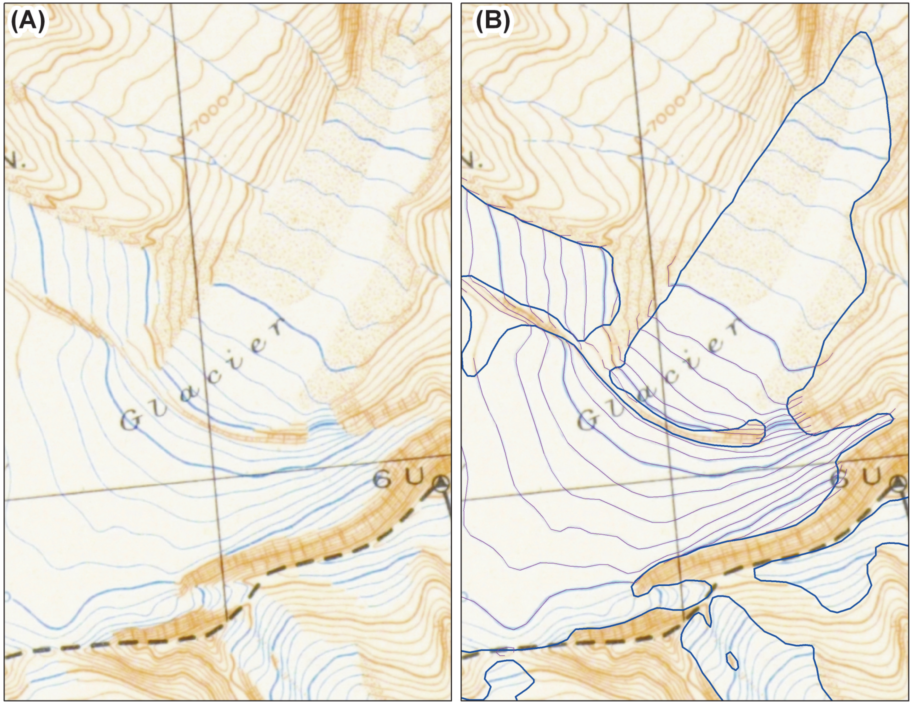

Fig. 4. Example of **(A)** a glacier on the IBCS maps and **(B)** digitized extents and contours.

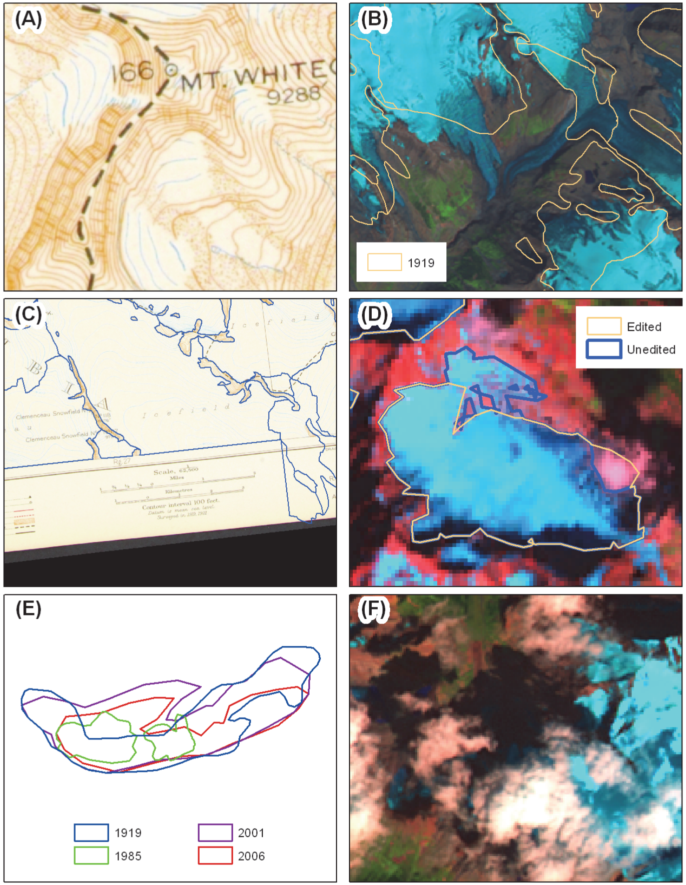

Fig. 5. Errors and problems associated with the glacier extents: **(A)** offset 1919 glacier contours; **(B)** mismapped 1919 extents; **(C)** cut off glaciers; **(D)** unedited 2001 extents; **(E)** mismapped 1985 and 1919 extents; and **(F)** shadow and cloud cover.

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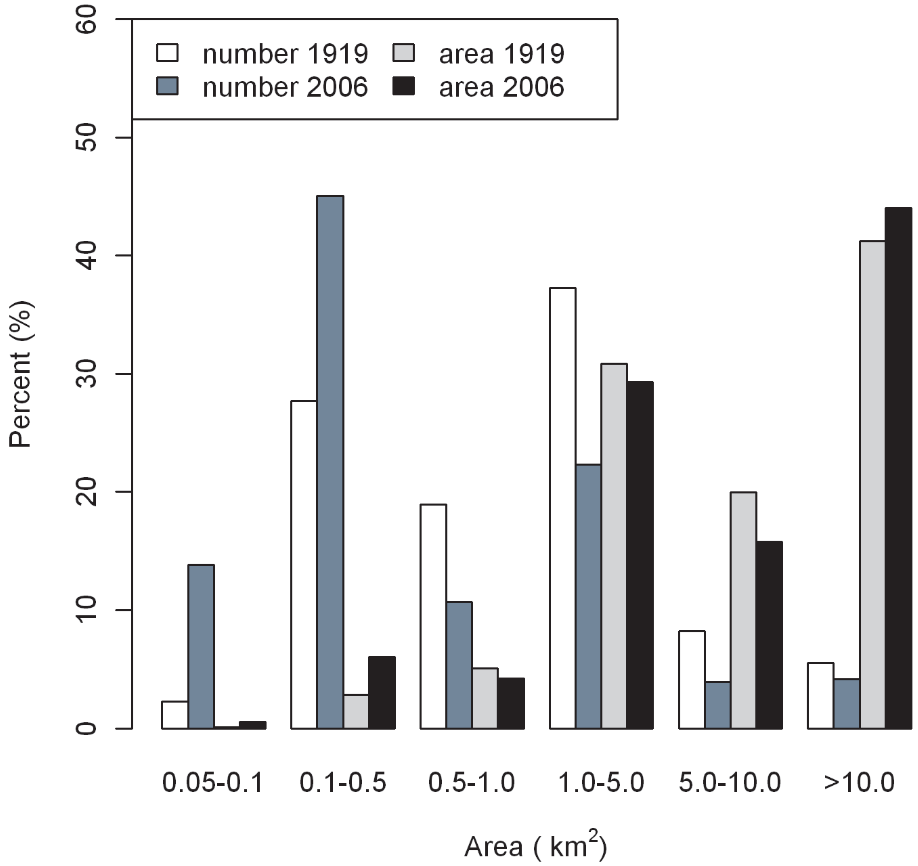

Fig. 6. Size class distribution of glaciers in the Canadian Rocky Mountains for the years 1919 and 2006, by percent glacier number and area.

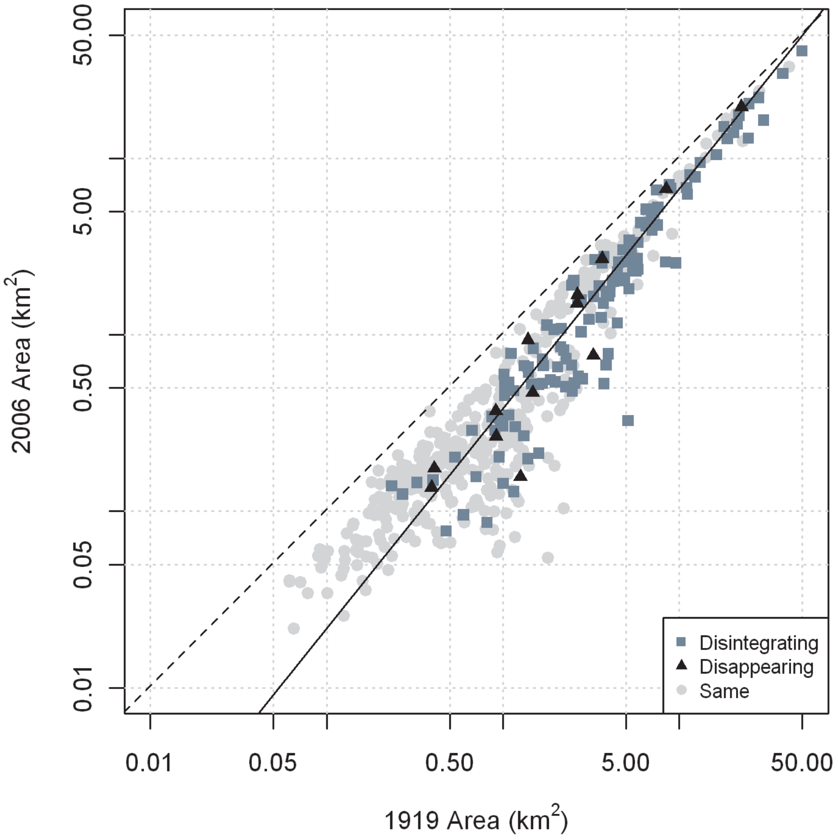

Fig. 7. Log-log plot of 2006 glacier area versus 1919 glacier area. Points are separated into groups based on an increase (disintegrating), decrease (disappearing), or no change (same) in the number of ice masses within a flowshed. The solid line is a linear model fitted to the data described by Eq. (1). The one-to-one line is dashed.

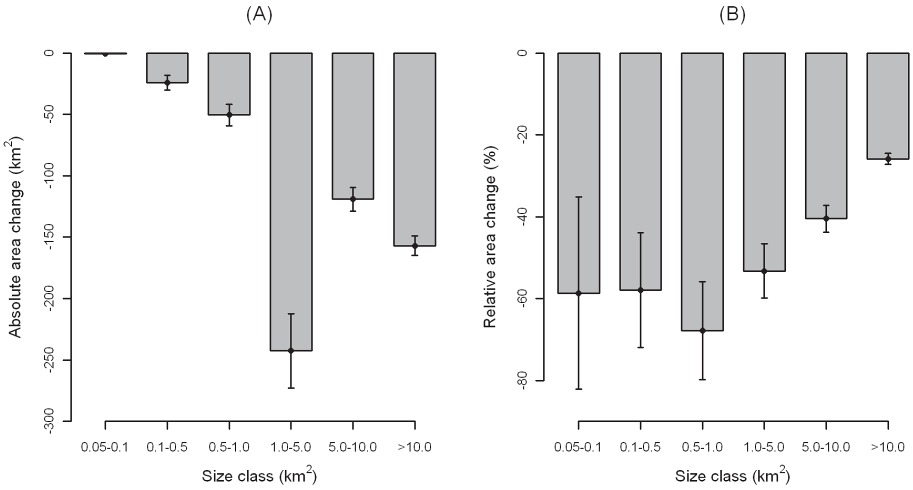

Fig. 8. Total **(A)** absolute and **(B)** relative area change by size class of glaciers in the Canadian Rocky Mountains between 1919 and 2006. Error bars are shown representing the mean error for each size class.

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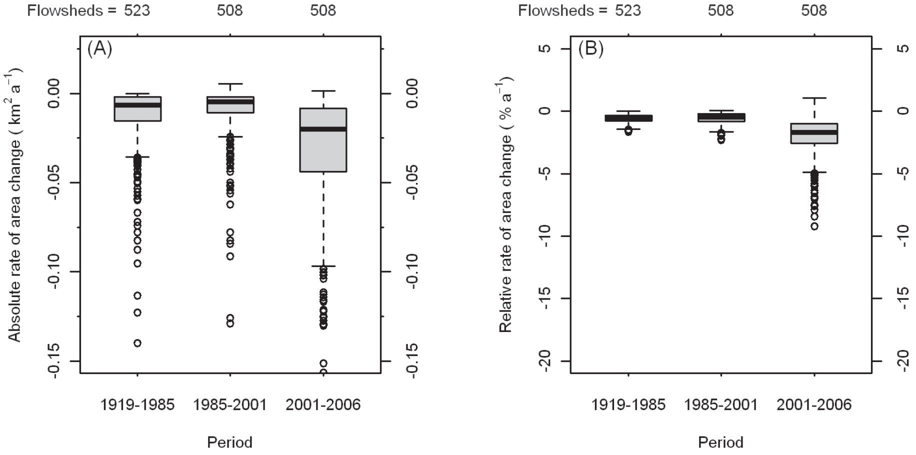

Fig. 9. **(A)** Absolute and **(B)** relative rates of area change for the Canadian Rocky Mountains, over three periods from 1919 to 2006. Boxes represent the first and third quartiles with the horizontal black line as the median. The whiskers represent the data extremes (5th and 95th percentile) and the circles are outliers.

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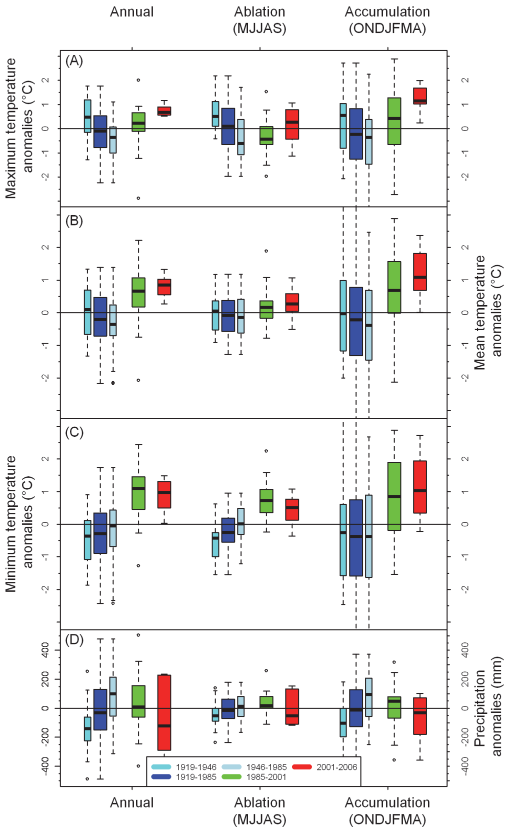

Fig. 10. Regional **(A)** maximum, **(B)** mean, and **(C)** minimum temperature anomalies calculated for the average annual, ablation, and accumulation seasons for the periods 1919–1985, 1985–2001, and 2001–2006. **(D)** Precipitation anomalies calculated from the precipitation totaled over the hydrologic year (annual), and ablation and accumulation seasons for the same periods. The climatic mean is based on the period 1919–2006. Additional periods, 1919–1946 and 1946–1985, are included to show the change in climate over the winter of 1945/1946.