

1 **Glacier change in the Cariboo Mountains, British**
2 **Columbia, Canada (1952-2005)**

3

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8

9 **Abstract**

10 We applied photogrammetric methods with aerial photography from 11 different years
11 between 1946 and 2005 to assess changes in area and volume 33 glaciers in the Cariboo
12 Mountains of British Columbia for the latter half of the twentieth century. These are used
13 to identify changes in extent and elevation primarily for the periods 1952-1985, 1985-
14 2005 and 1952-2005. All glaciers receded during the period 1952-2005; area retreat
15 averaged $-0.19 \pm 0.05\% \text{ a}^{-1}$. From 1952 to 1985, nine glaciers advanced; following 1985,
16 retreat rates accelerated to $-0.41 \pm 0.12\% \text{ a}^{-1}$. Thinning rates of a subset of seven glaciers
17 likewise accelerated, from $-0.14 \pm 0.04 \text{ m w.e. a}^{-1}$ (1952-1985) to $-0.50 \pm 0.07 \text{ m w.e. a}^{-1}$
18 for the period 1985-2005. Temperatures increased from the earlier to the latter period for
19 the ablation ($+0.38^\circ\text{C}$) and accumulation ($+0.87^\circ\text{C}$) seasons, and average precipitation
20 decreased, particularly in the accumulation season (-32 mm , -3.2%). Our comparison of
21 surface area change with glacier morphometry corroborates previous studies that show
22 primary relations between extent change and surface area. We also find that the strength
23 and sign of these relations varied for different epochs. Our results also indicate that the
24 1985 glacier extent for the study area, reported previously by other studies, may be
25 slightly overestimated due to errant mapping of late-lying snow cover.

26

27 **1 Introduction**

1 Glaciers are important components of the hydrologic system. They contribute meltwater
2 along with organic and inorganic materials to freshwater systems (Bogdal et al., 2009;
3 Hood et al., 2009; Moore et al., 2009; Marshall et al., 2011). These inputs, along with
4 downstream impacts, are altered when glaciers undergo changes in extent and volume.
5 As glaciers and ice caps (GIC; all glaciers outside of the Antarctic and Greenland ice
6 sheets) lose volume, sea level rises (Radić and Hock, 2011). The largest GIC
7 contributions to sea level rise include the Canadian Arctic Archipelago and Gulf of
8 Alaska regions (Gardner et al., 2011; Berthier et al., 2010), but recent work demonstrates
9 that, collectively, small glaciers (<1 km²) contribute a significant amount to total GIC
10 volume (Bahr and Radić, 2012).

11 Recent studies of glacier change use a variety of remotely-sensed products that include
12 aerial photography (Koblet et al., 2010; Tennant et al., 2012), satellite imagery (Paul et
13 al., 2004; Berthier et al., 2010), and laser altimetry (Sapiano et al., 1998; Arendt et al.,
14 2002). Typically these studies employ a combination of geomatic data to assess changes
15 in glaciers for a particular region (Schiefer et al., 2007; Abermann et al., 2009; Bolch et
16 al., 2010). Comprehensive inventories of glacier extent and change (e.g., Bolch et al.,
17 2010), and measurement of glacier volume change of large regions (e.g., Schiefer et al.,
18 2007) primarily rely on satellite borne instruments. Such analysis is therefore limited to
19 the last 30 years.

20 Aerial photography can be used to extend glacier change documentation by up to three
21 decades prior to the beginning of the satellite era. In British Columbia, repeat aerial
22 surveys have been approximately decadal and thus an opportunity exists to assess multi-
23 decadal changes in the area and volume of alpine glaciers. Debeer and Sharp (2007), for
24 example, combined aerial photography and satellite imagery to assess changes in glacier
25 cover in the southern Canadian Cordillera over the second half of the twentieth century.
26 In particular, they noted negligible change of small glaciers in their study. Our study
27 builds on Debeer and Sharp (2007) by expanding the spatial domain over which glacier
28 change is evaluated and by increasing the number of epochs over which these changes
29 can be compared to the instrumental record.

1 In this study we use aerial photogrammetry to investigate the extent and volume change
2 of a subset of glaciers in western Canada for the periods 1952-1970, 1970-1985, and
3 1985-2005. The use of aerial photography thus provides a method to temporally extend
4 the glacier inventory studies of Schiefer et al. (2007) and Bolch et al. (2010), and in
5 addition an independent check against glacier mapping using lower-resolution satellite
6 imagery.

7 The objectives of this study are to: 1) document the extent and volume change of a subset
8 of glaciers in the Cariboo Mountains of British Columbia (BC); and 2) assess the
9 climatological conditions that could explain observed glacier change in the study area.

10 **1.1. Study area and previous work**

11 The Cariboo Mountains are the northernmost range of the Columbia Mountains of BC,
12 Canada (Fig. 1). The climate of the Cariboo Mountains is transitional, wetter than the
13 Rocky Mountains to the east, and drier than the Coast Mountains. Total annual
14 precipitation (1971-2000 climate normals) averages 1014 and 679 mm on the windward
15 (Barkerville, BC) and lee (McBride, BC) sides of the Cariboo Mountains, and annual
16 temperature averages 1.9 and 4.4°C respectively (Environment Canada, 2012).

17 Annual length change of Castle Creek Glacier in the Cariboo Mountains is more closely
18 related to changes of glaciers in the Coast Mountains than those of the Rocky Mountains
19 (Beedle et al., 2009). Meltwater from the majority of glaciers in the Cariboo Mountains
20 contributes to the Fraser River; however, some glaciers in the Premier Range (a Cariboo
21 Mountains subrange) contribute to the Columbia River (Fig. 1). Maurer et al. (2012)
22 found that glaciers of the Cariboo Mountains nearly reached their Holocene maximum
23 extents around 2.73-2.49 ka and that major retreat of the glaciers did not begin until the
24 early 20th century. Luckman et al. (1987) showed that some glaciers of the Premier Range
25 advanced in the 1960s and 1970s in response to decreased temperatures and increased
26 winter precipitation. Bolch et al. (2010) completed the first satellite inventory of glaciers
27 in western Canada, identifying 536 glaciers in the Cariboo Mountains (2005) with a total
28 surface area of 731 km². Cariboo Mountains glaciers lost 7.06 km³ of ice at a rate of -0.58
29 m water equivalent (w.e.) a⁻¹ during the period 1985-1999 (Schiefer et al., 2007).

30

1 **2. Methods**

2 **2.1. Imagery and supplemental data**

3 We measured glacier extent and surface elevation change from aerial photographs
4 obtained from the British Columbia Government and Canada National Air Photo Library
5 (Table 1). Imagery prior to 2005 was scanned at a resolution of 12-14 μm from
6 diapositives or negatives using a photogrammetric scanner whereas imagery from 2005
7 was available as digital aerial triangulation (AT) scans (digital photos with available
8 exterior orientation; BC Ministry of Environment, 1998). Ground sampling distance
9 ranges from 0.2 to 1.1 m depending on scanning resolution and image scale. Most photos
10 were taken in late summer, but dates range from mid-July to late-September. We used all
11 images to estimate glacier length and area change, whereas only those from 1946, 1952,
12 1984, 1985, and 2005 were used to determine surface-elevation change. As photos for
13 each subregion were taken in different years, we thus report a mean area-weighted year:
14 1952 for photos taken in 1946, 1952, or 1955; 1970 for those of 1967, 1970, or 1971; and
15 1985 for those of 1984 or 1985. All annual rates of extent or volume change are
16 calculated using the actual duration between images. We report extent change of glaciers
17 within three intervals (1952-1970, 1970-1985, and 1985-2005) and surface-elevation
18 change for two epochs (1952-1985 and 1985-2005).

19 We use ClimateWNA (Wang et al., 2012) to assess the variability in temperature and
20 precipitation during the periods for which we measure glacier extent and surface-
21 elevation change. The ClimateWNA v4.72 program
22 (<http://www.genetics.forestry.ubc.ca/cfcg/ClimateWNA/ClimateWNA.html>) interpolates
23 and extracts climate data for specific locations for western North America, relying on
24 downscaled PRISM (Daly et al., 2002) and historical data (Mitchell and Jones, 2005) to
25 generate monthly time series of temperature and precipitation. Refer to Wang et al.
26 (2012) for details. We use averaged ClimateWNA output for points along the center-line
27 every 100 m in elevation for all 33 glaciers ($n = 212$) to estimate Cariboo Mountains
28 glacier climatology, and for glaciers of the Castle Creek region ($n = 47$), Quanstrom
29 region ($n = 62$), and Premier region ($n = 103$) to estimate sub-regional climatology. We
30 compare monthly temperature precipitation data from ClimateWNA with measurements

1 at Castle Creek Glacier (Déry et al., 2010) for 2009-2011 to estimate the ability of
2 ClimateWNA to represent conditions at high elevations in the Cariboo Mountains.

3 To investigate dominant synoptic patterns over the Cariboo Mountains, we use the
4 National Centers for Environmental Protection/National Center for Atmospheric
5 Research (NCEP/NCAR) reanalysis data (Kalnay et al., 1996) of 700 hPa geopotential
6 height anomalies. The 700 hPa geopotential surface provides a good indicator of general
7 atmospheric conditions in the middle troposphere (~3000 m), an elevation just above the
8 uppermost extent of most glaciers in the Cariboo Mountains. We assess climatic
9 conditions for balance years (October-September), and for ablation and accumulation
10 seasons, defined as June-September and October-May, respectively.

11 **2.2. Photogrammetry**

12 We used the Vr Mapping photogrammetry software suite (Cardinal Systems LLC) to
13 create stereo models from aerial photos. Exterior orientation for the models was derived
14 from tie points and common ground control points (GCP) horizontally and vertically
15 distributed throughout the photos (Schiefer and Gilbert, 2007; Barrand et al., 2009).
16 Within each subregion we used common GCPs to reduce systematic positional errors
17 (Kääb & Vollmer, 2000; Schiefer and Gilbert, 2007; Schiefer et al., 2007). GCPs
18 consisted of stable bedrock features or boulders obtained from aerial triangulated stereo
19 models (BC Ministry of Environment, 1998).

20 Eleven check patches, located on stable surfaces around each glacier region (Fig. 2), were
21 used to quantify the relative accuracy of the stereo models (Fig. 3). Each check patch is
22 comprised of 25 individual checkpoints in a five-meter grid; we estimated systematic bias
23 of stereo models from the mean residuals of the check patches. Trend surfaces were
24 created from these 11 mean residuals and used to apply a correction for glacier surface-
25 elevation measurements.

26 **2.3. Glacier subset selection**

27 With the exception of 2005, glaciers of the Cariboo Mountains were not comprehensively
28 photographed in any given year, and we thus concentrate our study on three subregions of
29 the Cariboo Mountains with suitable photographic coverage: 1) the Castle Creek Glacier

1 area; 2) the Quanstrom Mountain area; and 3) the Premier Range (Figs. 1 and 2). We
2 selected our subset of glaciers based on: 1) availability of imagery, both in terms of
3 temporal resolution and spatial scale; 2) snow cover and contrast; and 3)
4 representativeness based on average glacier morphometry of Cariboo Mountain glaciers
5 presented in Bolch et al. (2010). Snowcover and poor contrast of older aerial photography
6 reduce potential glaciers for study (Table 1). Sun angle with respect to glacier aspect and
7 slope leads to local areas of high reflectivity and an absence of contrast, particularly for
8 some south-facing glaciers. We omitted glaciers with these issues in our selection of a
9 subset.

10 Within the three Cariboo Mountains subregions, we selected 33 glaciers representing five
11 size classes (0.1-0.5, 0.5-1.0, 1.0-5.0, 5.0-10.0, and >10.0 km²). We used surface area as
12 our primary criterion to select glaciers as many studies find it to be the key morphometric
13 determinant of glacier extent change (e.g., Serandbrei-Barbero et al., 1999; Hoelzle et al.,
14 2003; Paul et al., 2004; Andreassen et al., 2008; Bolch et al., 2010; Paul and Andreassen,
15 2009). Our analysis oversampled glaciers in the largest size class as these glaciers likely
16 play a dominant role in regional volume change and meltwater contributions to their
17 respective watersheds (e.g., Arendt et al., 2006; DeBeer and Sharp, 2007; Paul and
18 Haeberli, 2008). All ice masses with the exception of Kiwa Glacier (glacier 32 in Fig. 2
19 and Table 3) are land-terminating glaciers.

20 **2.4. Data collection and analysis**

21 We collected glacier extents and point measurements of surface elevation directly from
22 the stereo models following the methods described elsewhere (Tennant et al., 2013;
23 Beedle et al., (2014). This approach allowed us to collect elevation and points while
24 viewing the 3D models with polarized glasses and a shutter screen. The primary
25 advantage of this approach is that it minimizes common errors that can occur with
26 automated digital elevation model extraction methods (e.g. pixel mismatch and
27 interpolation errors). Complete glacier outlines were mapped for 2005, and glacier
28 extents were updated for previous years only below the transient snowline (TSL), thus
29 eliminating errantly mapping seasonal snow cover as glacierized area (e.g., Koblet et al.,
30 2010). Delineation of planimetric glacier area above the TSL is problematic as seasonal

1 snow cover masks the glacier margin, and can erroneously inflate estimates of glacier
2 surface area. Mapping of ice divides relied on surface elevation and surface features such
3 as crevasses and runnels; these divides were held constant in order to compare
4 dimensional changes for a given ice body through time. Extent-change analysis was
5 made for different glacier subsets by epoch based on aerial photo coverage and
6 snowcover. Collectively, our analysis allows us to compare area change for 33 glaciers
7 for the epochs 1952-1985, 1985-2005, and 1952-2005 (33-glacier subset), and for 26
8 glaciers in the additional epochs 1952-1970, and 1970-1985 (26-glacier subset).

9 Poor contrast and snowcover limit our analysis of glacier surface elevation change to
10 seven glaciers for the periods 1952-1985, 1985-2005, and 1952-2005. For these glaciers,
11 we measured surface elevation on a 100 m grid for large glaciers ($>1 \text{ km}^2$) and on a 50 m
12 grid for small glaciers ($< 1 \text{ km}^2$). Poor contrast in the earliest photographs inhibited data
13 collection over portions of glacier accumulation zones for four of the seven glaciers. In
14 these areas, we extrapolate from the three highest elevation bins where we have
15 measurements, assigning the average surface-elevation change of these observations to
16 the bins with missing values. This assumption was necessary only for periods that rely on
17 the earliest year of photography (1952); missing data total a maximum of 27% of total
18 glacier surface area.

19 To calculate glacier-wide volume change from point measurements, we multiplied
20 average elevation change for each 50 m elevation bin and summed over the entire glacier
21 surface. Elevation bins and glacier surface were derived from epoch-specific glacier
22 hypsometries created from the same point measurements. Where poor contrast led to an
23 absence of measurements in the accumulation area, we used surface-elevation
24 measurements for that elevation bin from the stereo model of a prior or subsequent year.
25 This approach assumes that surface elevation and extent underwent negligible change, an
26 assumption that would be inappropriate in the rapidly changing ablation zones, but one
27 that is more likely in the accumulation zones where this assumption was applied. We
28 calculated glacier wide average thickness change based on the average of the two extents
29 that define a given period (e.g., Arendt et al., 2002; Barrand et al., 2010). All values
30 presented in water equivalent (w.e.) are calculated by assuming a density of 900 kg m^{-3} in
31 the ablation area and 750 kg m^{-3} in the accumulation area (e.g., Huss, 2013; Beedle et al.,

1 2014); ablation and accumulation areas are defined by each glacier’s median elevation
2 (Table 2).

3 To estimate regional (Cariboo Mountains) glacier extent change, we extrapolated from
4 measurements of our subset of studied glaciers using the average rates of relative extent
5 change by size class for different periods. We used two methods to estimate Cariboo
6 Mountains surface-elevation change: first, the average surface-elevation change of our
7 subset of seven glaciers; and second, the average gradient of surface-elevation change
8 with elevation, defined as the average of all measurements within each 50-meter bin, and
9 integrated it with the Cariboo Mountains glacier hypsometry of 1985. We compare
10 extrapolated values with results from recent work that included volume change (Schiefer
11 et al., 2007) and extent change (Bolch et al., 2010) of Cariboo Mountains glaciers.

12 **2.5. Error analysis**

13 We estimated error in glacier extent and extent change based on a buffer approach
14 (Granshaw and Fountain, 2006). Our buffer (± 5 pixels) yields widths of ~ 5.5 to 1.3 m,
15 depending on image resolution. Error in extent change is calculated as the root mean
16 squared error (RMSE) of the error estimates for the years that define a given period.
17 Average errors for the 33-glacier subset range from 0.8 - 2.4% for extents, and from 2.3 -
18 3.6% for extent change. These errors vary depending on image resolution (see Table 1)
19 and glacier dimensions.

20 We used the standard deviation of 275 check points in 11 check patches to estimate error
21 in our measurements of surface-elevation change ($E_{\Delta Z}$). To account for greater
22 uncertainty over surfaces with reduced contrast, we added an error of ± 5 m for
23 measurements above the TSL. In cases where measurements are absent due to poor
24 contrast, we increased this added error term to ± 10 m (e.g., Tennant and Menounos,
25 2013). Error in measurements of surface-elevation change in the ablation area is 1σ of
26 check points, whereas for the accumulation zone it is the quadrature sum of 1σ of check
27 points (E_1) and the added error of ± 5 or 10 m for reduced contrast (E_2):

$$28 \quad E_{\Delta Z} = \sqrt{E_1^2 + E_2^2} \quad (1)$$

1 Converting to water equivalent units through density assumptions imparts an additional
2 error term. To estimate error in the density assumption of 750 kg m^{-3} for the
3 accumulation zone we used a range of possible values for accumulation-zone density
4 ($600\text{-}900 \text{ kg m}^{-3}$). We estimate error in our measurements of surface-elevation change in
5 water equivalent units ($E_{\Delta Z \text{ w.e.}}$) as:

$$6 \quad E_{\Delta Z \text{ w.e.}} = \sqrt{E_{\Delta Z}^2 \rho^2 + E_{\rho}^2 \Delta Z^2} \quad (2)$$

7 where ρ is density expressed as a water-equivalent conversion factor (0.9 in the ablation
8 zone, 0.75 in the accumulation zone), and E_{ρ} is the error in our density assumptions,
9 assumed to be 0 in the ablation area and 0.15 in the accumulation zone.

10 We estimate volume change error (E_{VOL}) after Barrand et al. (2010) as:

$$11 \quad E_{VOL} = \sqrt{\sum_1^{bin} (E_{bin} A_{bin})} \quad (3)$$

12

13 where E_{bin} is the error ($E_{\Delta Z \text{ w.e.}}$) and A_{bin} is the surface area of each 50 m bin.

14 Previous work indicated a spatial correlation of 1000 m in photogrammetric DEMs
15 (Rolstad et al., 2009), and others have calculated a number of independent measurements
16 (n) assuming a correlation scale of 1000 m (Barrand et al., 2010). We calculated degrees
17 of freedom for each glacier from point measurements of surface-elevation change in
18 epochs with complete spatial coverage. Using the Incremental Spatial Autocorrelation
19 tool in ArcGIS 10.1 we calculated correlation distances that range from 350 to 2000 m,
20 yielding effective degrees of freedom that range from 1 to 5.

21 We used cross-validation to test the accuracy of our extrapolation of Cariboo Mountains
22 glacier extent and surface-elevation change. In our test of glacier extent extrapolation, we
23 partitioned the 26-glacier subset into four scenarios where we withheld 75, 50, and 25%
24 of the individual glaciers as a validation set and retained the remainder as a training set.
25 Set selection was randomized within each size class, ensuring each set retained glaciers
26 of varying size. Each of the three scenarios was applied to observations in five epochs:
27 1952-1970, 1970-1985, 1985-2005, 1952-1985, and 1952-2005. We used the standard
28 deviation of these 15 test cases ($\pm 4.7\%$) as an estimate of error in our extrapolation of the

1 extent of all Cariboo Mountains glaciers. To estimate error in our extrapolation of
2 surface-elevation change, we partitioned our seven glacier subset into two scenarios
3 where we withheld three and four individual glaciers as a validation set and retain the
4 remainder as a training set. Each scenario was applied to observations in three epochs:
5 1952-1985, 1985-2005, and 1952-2005. We used the variability of these six test cases to
6 estimate error in our extrapolation of surface-elevation change using two methods: 1)
7 mean annual rate of surface elevation change of the glacier subset (± 0.077 m w.e. a^{-1});
8 and 2) mean surface-elevation change within each collective 50 m elevation bin for the
9 glacier subset (± 0.089 m w.e. a^{-1}).

10

11 **3. Results**

12 **3.1. Regional representativeness**

13 As expected, our glacier subset under samples ice masses of the Cariboo Mountains in all
14 size classes except the largest size class (Fig. 4). Most glaciers in the Cariboo Mountains
15 (40%) fall in the 1.0-5.0 km^2 size class compared to 20% in our sample. In contrast, our
16 subset contains 61% glaciers exceeding 5.0 km^2 compared to 21% for the Cariboo
17 Mountains. Eliminating four of the five largest glaciers from our 33-glacier subset
18 (glaciers 30-33; Table 3) would result in a size-class distribution that is nearly identical to
19 glaciers in the Cariboo Mountains.

20 Our glacier subset also oversamples higher elevations (Fig. 5). Area-altitude distribution
21 of glaciers in the Premier range, for example, are higher than the average elevation of
22 glacier in the Cariboo Mountains whereas the hypsometry of our glacier subset from the
23 Castle and Quanstrom areas are more similar to the total glacierized area of the Cariboo
24 Mountains.

25 Glaciers in our study also more commonly face north, northeast, and southwest (Fig. 6).
26 Cariboo Mountains glaciers have an average slope of 21.1° whereas our subset has an
27 average slope of 18.7° ; these differences, however, are not statistically significant.

28 **3.2. Extent change**

1 Between 1952-2005, glaciers lost $15.11 \pm 1.89 \text{ km}^2$ ($-10.6 \pm 2.9\%$) of their surface area
2 (Table 3). Relative area change varied by subregion, with losses of $-11.2 \pm 2.7\%$,
3 $-16.4 \pm 2.0\%$, and $-4.2 \pm 3.9\%$ for the Castle, Quanstrom, and Premier regions
4 respectively. Absolute area change by size class over the same period varied from -
5 $6.2 \pm 3.3\%$ ($0.5\text{-}1.0 \text{ km}^2$) to $-13.9 \pm 1.1\%$ ($5.0\text{-}10 \text{ km}^2$). Individual glacier area loss
6 varied from -0.5 ± 1.6 to $-31.7 \pm 1.4\%$. Recession for 22 of the 33 glaciers exceeded
7 the uncertainties in the data. Absolute extent change is dominated by three of the
8 largest glaciers (glaciers 28, 31, and 33), which comprise 50% of the total subset
9 extent change for the period.

10 While glaciers on average shrank during the period 1952-2005, their change during
11 intervening epochs was more complex (Table 3 and Fig. 7). Over the period 1952-1970,
12 for example, five of 26 glaciers advanced, seven receded, and 14 did not significantly
13 change. Between the years 1970 and 1985, two of 26 glaciers advanced, eight shrank, and
14 the area of 16 glaciers did not change. For the cumulative period 1952-1985 nine glaciers
15 advanced, 12 receded, and 11 had no discernable extent change.

16 Glaciers that advanced were generally shorter, smaller, steeper, and had higher median
17 and minimum elevations than glaciers that receded (Table 4). Glaciers that negligibly
18 changed tended to be steep, but were longer than those glaciers that advanced. Glaciers
19 that changed little were also higher and flowed over a greater elevation range than
20 advancing ones. Receding glaciers all had northerly aspects, whereas those that advanced
21 or did not change had no dominant aspect.

22 After 1985, all glaciers throughout the region shrank (Fig. 7). The average rate of area
23 change increased from $-0.05 \pm 0.10\% \text{ a}^{-1}$ from 1952-1985, to $-0.41 \pm 0.12\% \text{ a}^{-1}$ from
24 1985-2005. Rates of area change averaged $+0.03 \pm 0.18\% \text{ a}^{-1}$ for 1952-1970, $-0.08 \pm$
25 $0.13\% \text{ a}^{-1}$ for 1970-1985, and $-0.40 \pm 0.10\% \text{ a}^{-1}$ from 1985-2005. During the period 1985-
26 2005, 30 glaciers receded, and the area of two glaciers did not change. Total surface area
27 change of the period 1985-2005 was $-8.39 \pm 1.51 \text{ km}^2$, or $-6.2 \pm 2.3\%$ (Table 3).

28 Extrapolating from the Bolch et al. (2010) inventory of 2005 (731 km^2) using relative
29 area change of our 26-glacier subset and based on area loss per size class, we estimated
30 that in 1952, the Cariboo Mountains contained a glacierized area of $824 \pm 39 \text{ km}^2$. By

1 1970 glacier cover declined to $805 \pm 38 \text{ km}^2$, and continued to shrink to $785 \pm 37 \text{ km}^2$ by
2 1985.

3 We directly compare glacier extent and extent change (1985-2005) for 28 glaciers
4 common to the Bolch et al. (2010) inventory and this study (Fig. 8). The Bolch et al.
5 inventory relies on glacier extents mapped by the British Columbia Government Terrain
6 Resource Inventory Management (TRIM) program from 1980s aerial photography and
7 Landsat imagery from 2003-2007. The 2005 extents of this inventory, created through a
8 semi-automated process, average 2% larger than our extents manually digitized from
9 aerial photographs with much higher resolution. However, the Bolch et al. (2010)
10 inventory uses an area-weighted date (2005); the actual date of imagery covering the
11 Cariboo Mountains is from 2006. Relative area change for the period 1985-2005
12 averaged $\sim 0.3\% \text{ a}^{-1}$ for this 28-glacier subset, and thus the Bolch et al. (2010) inventory,
13 based on 2006 imagery, will not significantly differ from our measurements from 2005
14 aerial photos. This provides evidence of the quality of the 2005 inventory and the
15 precision of the method used by Bolch et al. (2010). The 1985 TRIM extents, however,
16 digitized manually by the province of British Columbia from the same aerial photographs
17 we use here, average 5% larger than our extents. Late-lying snow is prevalent in the 1984
18 and 1985 photographs, but reference to additional photographs in years with a higher
19 snowline helped us distinguish snowfields from glacierized area. The TRIM mapping
20 included some late-lying snow as glacier, resulting in overestimation of 1985 extents in
21 the TRIM dataset, by approximately 5%, and thus led to more surface-area loss reported
22 in the Bolch et al. (2010) inventory than we find for the 28 glaciers of this comparison.
23 However, the average change that we observe during the epoch 1985-2005 for our study
24 and that of Bolch et al., (2010) is not statistically different.

25 Based on the extrapolation procedure described above, we estimate a net change of -53
26 km^2 (-6.8%) for the period 1985-2005 compared to -114 km^2 (-13.5%) of Bolch et al.
27 (2010). We estimate Cariboo Mountains glacier extent to have been $785 \pm 37 \text{ km}^2$ in
28 1985, versus 845 km^2 reported by Bolch et al., (2010), a difference of 7.7%. The Cariboo
29 Mountains glacierized area for 1952 was $824 \pm 39 \text{ km}^2$, still 2.5% less than the 845 km^2
30 of the 1985 TRIM extents used in previous work (Schiefer et al., 2007; Bolch et al.,
31 2010). Our results thus demonstrate that glacier loss during the period 1985-2005 was

1 higher than during previous epochs, but that the absolute surface area lost in this period
2 may have been overestimated in previous studies.

3 The relation between area change and glacier morphometry temporally varies (Table 5).
4 For three periods - 1952-1985, 1985-2005, and 1952-2005 – absolute area change
5 correlates ($p < 0.05$) negatively with glacier length and area, indicating that the larger
6 glaciers in absolute terms lost more surface area in all periods. The relation between
7 relative area change and both length and area varies with time. For the period 1952-1985
8 we find r -values of -0.235 and -0.210 for length and area respectively, and these
9 correlations for length and area change to 0.328 ($p < 0.10$) and 0.316 ($p < 0.10$) for the
10 period 1985-2005. Large glaciers thus lost more relative area in the earlier period,
11 whereas small glaciers lost more relative area in the latter period. Average glacier surface
12 slope is correlated with absolute and relative area change in all periods, except for
13 relative area change from 1985-2005, indicating steeper glaciers generally lost less
14 absolute and relative surface area, except during the latter period when there was no
15 correlation. Median glacier elevation is correlated with absolute area change for the
16 period 1952-1985 ($r = 0.358$, $p < 0.05$) and relative area change for the period 1952-2005
17 ($r = 0.487$, $p < 0.05$) indicating that glaciers with more surface area at higher elevations
18 experienced less area change in these two periods.

19 **3.3. Volume change**

20 Over the period 1952-2005, the seven glaciers of our study lost $-0.480 \pm 0.051 \text{ km}^3 \text{ w.e.}$
21 Volume loss during the first period (1952-1985) totaled $-0.195 \pm 0.059 \text{ km}^3 \text{ w.e.}$, and this
22 loss accelerated to $-0.345 \pm 0.048 \text{ km}^3 \text{ w.e.}$ during the later period (1985-2005). These
23 volume losses correspond to respective mean thinning rates of $-0.14 \pm 0.043 \text{ m w.e. a}^{-1}$
24 and $-0.50 \pm 0.07 \text{ m w.e. a}^{-1}$ (Table 6 and Fig. 9). Net thinning rates over the period 1952
25 to 2005 averaged $-0.23 \pm 0.02 \text{ m w.e. a}^{-1}$. Two glaciers, both of which advanced over the
26 same period, markedly thickened between 1952-1985 (Table 6). Both of these glaciers
27 thinned after 1985, but experienced little net change from 1952-2005. Five glaciers
28 continuously thinned and receded.

29 Extrapolation of these thinning rates to unmeasured glaciers in the Cariboo Mountains
30 yields volume losses of -4.027 ± 2.044 and $-7.580 \pm 1.167 \text{ km}^3 \text{ w.e.}$ for the periods 1952-

1 1985 and 1985-2005 respectively. We obtain lower estimates of volume change ($-2.312 \pm$
2 2.170 and $-6.242 \pm 1.315 \text{ km}^3 \text{ w.e}$) using elevation-averaged surface elevation change
3 measurements from these seven glaciers.

4 **3.4. Relation to climate**

5 Surface temperature increased during the period of study, particularly after 1985 (Fig.
6 10). From the earlier (1952-1985) to the latter epoch (1986-2005), average temperatures
7 increased by $+0.38$ and $+0.87 \text{ }^\circ\text{C}$ for the ablation and accumulation season respectively.

8 Accumulation season and annual precipitation decreased during the period of study, but
9 little change occurred during the ablation season (Fig. 11). From the earlier (1952-1985)
10 to the latter period (1986-2005), accumulation-season and annual precipitation decreased
11 by -32 mm (-3.2%) and -44 mm (-3.0%) respectively, minor changes that are
12 overwhelmed by large inter-annual variability.

13 Geopotential height (700 hPa) anomalies, based on 1952-2005 mean fields, reveal an area
14 of persistent low pressure in western Canada during the accumulation and ablation
15 seasons for the periods 1952-1970 and 1971-1985 (Fig. 12). These low-pressure
16 anomalies were centered over the Yukon Territory and northern BC from 1952-1970.
17 These areas of low pressure weakened during the period 1971-1985 with a prominent
18 trough along the Coast Mountains (ablation season) and diffuse area of anomalously low
19 pressure over much of central North America (accumulation season). A marked change in
20 circulation occurred for the later period with anomalously high pressure present during
21 the period 1986-2005, with ridges over south central Alaska (ablation season) and off the
22 coast of northern BC and southeastern Alaska (accumulation season).

23 These synoptic conditions broadly accord with the Pacific Decadal Oscillation (PDO;
24 Mantua et al., 1997), a pattern of Pacific climate variability that persists for multiple
25 decades and plays a prominent role in determining glacier mass balance in northwest
26 North America (e.g., Bitz and Battisti, 1999). The earlier two periods (1950-1970 and
27 1971-1985) were largely or partially coincident with a cool phase of the PDO from 1947
28 to 1976. In contrast, the latest period (1985-2005) coincided with a warm phase of the
29 PDO from 1977 to at least the mid-1990s.

1

2 **4. Discussion**

3 **4.1. Regional representativeness**

4 Our glacier subset represents a compromise between regional representativeness and the
5 availability of suitable aerial photography. We oversampled large glaciers as they will
6 contribute most to volume change for a given region. While glaciers of the 1-5 km² size
7 class dominated volume change in the Cariboo Mountains for the period 1985-2005,
8 losses from large glaciers (>5 km²) were even more important for previous epochs. The
9 two largest glaciers for which we calculated volume change, for example, accounted for
10 94% of the total volume change for seven glaciers from 1952-1985, and 75% from 1985-
11 2005. Selection of a representative subset of glaciers for a region is difficult, especially
12 when glacier change is assessed over multiple epochs.

13 Most studies of glacier change note increased scatter of percent area change for smaller
14 glaciers (Serandbrei-Barbero et al., 1999; Kääb et al., 2001; Paul, 2002; Paul et al., 2004;
15 DeBeer and Sharp, 2007; Andreassen et al., 2008; Bolch, et al., 2010; Paul and
16 Andreassen, 2009). This scatter may arise from the influence of local topographic factors
17 (DeBeer and Sharp, 2007; Paul and Andreassen, 2009). Kääb et al. (2001) concluded that
18 this scatter could also be the result of using low-resolution satellite imagery, or from the
19 fast response times of small glaciers. Late-lying seasonal snow may also impact the
20 inferred relative area change of small glaciers, and could play a role in the observation of
21 increased scatter for smaller glaciers. To assess this factor we compared the standard
22 deviation in relative area change of the smallest glaciers as measured for 28 glaciers in
23 both Bolch et al. (2010) and in our study, which based on our analysis is less affected by
24 late-lying seasonal snow cover. The standard deviation of relative area change from
25 1985-2005 for the Bolch et al. (2010) inventory is 8.1% for the smallest glaciers (<1.0
26 km²), whereas in our study it is 5.8%. This difference is significant (F-test, $p < 0.05$); it
27 supports our hypothesis that late-lying seasonal snow plays a role in observations of
28 increased scatter for smaller glaciers, and that the TRIM mapping of 1985 glacier extents
29 errantly mapped seasonal snow cover as glacierized area.

30 **4.2. Area change**

1 Our results indicate net recession of Cariboo Mountains glaciers from 1952-2005,
2 consistent with other studies of glacier change in BC (DeBeer and Sharp, 2007; Brewis,
3 2012; Tennant et al., 2012; Tennant and Menounos, 2013). While net glacier change of
4 our 33-glacier subset over this period is negative ($-15.11 \pm 1.89 \text{ km}^2$ or $-10.6 \pm 2.9\%$),
5 recession for 11 of these glaciers did not exceed measurement error. Nine of these 11
6 glaciers advanced during the period 1952-1985.

7 Our finding of glacier advance in the period 1952-1985 accords with the advance in the
8 Premier Range described by Luckman et al. (1987) and with glacier expansion elsewhere
9 in BC during this period (Koch et al., 2009; Menounos et al., 2009; Brewis, 2012;
10 Tennant and Menounos, 2013). Studies that only determine net recession over a multi-
11 decadal period (e.g., DeBeer and Sharp, 2007; DeBeer and Sharp, 2009; Jiskoot et al.,
12 2009) may not capture minor advances like those of the present study.

13 During the period 1985-2005, glaciers shrank (mean relative area change per annum)
14 eight times faster than the period 1952-1985, and five times faster than 1970-1985 (Fig.
15 7). Annual recession of Castle Creek Glacier (glacier 28) increased from about -10 m a^{-1}
16 in the early-to-mid 1980s to about -40 m a^{-1} in the early-1990s (Beedle et al., 2009).
17 Tennant and Menounos (2013) also found increased recession rates for glaciers of the
18 Columbia Icefield of BC and Alberta, which increased after 1979 and again after 2000.

19 **4.3. Thickness change**

20 Observed thinning rates during the period 1952-2005 averaged $-0.23 \pm 0.12 \text{ m w.e. a}^{-1}$,
21 resulting in a net loss of $-0.48 \pm 0.05 \text{ km}^3 \text{ w.e.}$ (Table 6). This rate of thinning is
22 considerably less than long-term thinning rates for glaciers of the Columbia Icefield (-0.6
23 $\pm 0.3 \text{ m w.e. a}^{-1}$; Tennant and Menounos, 2013) and Alaskan glaciers ($-0.48 \pm 0.10 \text{ m}$
24 w.e. a^{-1} ; Berthier et al., 2010). However, our average thinning rate is similar to those
25 reported for nine North America glaciers for the period from the mid-1950s to the mid-
26 1990s, which range from $+0.01$ to -0.61 and average $-0.21 \text{ m w.e. a}^{-1}$ (Sapiano et al.,
27 1998).

28 From 1952-1985 thinning rates averaged $-0.14 \pm 0.16 \text{ m w.e. a}^{-1}$ and glaciers lost $-0.20 \pm$
29 $0.06 \text{ km}^3 \text{ w.e.}$ The two smallest glaciers of our study thickened and advanced over the

1 same period. Brewis (2012) also found that four of six glaciers in the Canoe River Basin
2 (Fig. 1) thickened and advanced during the period 1955-1970.

3 The post-1985 accelerated thinning of Cariboo Mountain glaciers agrees with other
4 studies of glacier change in northwest North America (e.g., Rasmussen and Conway,
5 2004; Brewis, 2012; Tennant and Menounos, 2013). Schiefer et al. (2007) found that over
6 the period 1985-1999, and using different density assumptions, glaciers of the Cariboo
7 Mountains thinned by a rate of $-0.58 \text{ m w.e. a}^{-1}$ and lost $-7.06 \text{ km}^3 \text{ w.e.}$ Using our two
8 different methods of extrapolation described in Sect. 3.3, our estimates yield comparable
9 estimates of ice loss ($-6.24 \pm 1.32 \text{ km}^3$ and $-7.58 \pm 1.17 \text{ km}^3$) for the Cariboo Mountains.

10 Unlike the period 1985-2005, our methods of extrapolation to Cariboo Mountains
11 glaciers yield significantly different volume change estimates for the period 1952-1985 ($-$
12 $4.03 \pm 2.04 \text{ km}^3$ versus $-2.31 \pm 2.17 \text{ km}^3$). This discrepancy could arise from time-
13 varying magnitude of ice dynamics leading to extrapolation from a small subset
14 performing poorly during epochs with higher surface mass balance and where some
15 glaciers advanced. We recommend further study of extrapolation of regional volume
16 change from a subset of glaciers, but with a more robust sample size to better constrain
17 regional variability of surface-elevation change.

18 **4.4. Relations of extent change to glacier morphometry**

19 Glacier surface area is the single morphometric parameter that commonly correlates with
20 extent change (Serandbrei-Barbero et al., 1999; Hoelzle et al., 2003; Paul et al., 2004;
21 Andreassen et al., 2008; Bolch et al., 2010; Paul and Andreassen, 2009). From 1985-
22 2005, we find average relative area change of -11.2, -9.3, -7.5, -5.4, and -5.4% for our
23 five size classes, arranged from smallest to largest (Table 3). Surface area and relative
24 area change during the period 1985-2005 are weakly correlated ($p < 0.1$) indicating
25 generally more relative area change for smaller glaciers (Table 5). However, from 1952-
26 1985, a period with reduced rates of recession or advance, this does not apply; average
27 relative area change was -2.5, +3.4, -4.6, -9.0, and -4.1% for the same size classes, and
28 the r -value (not significant) is negative. It appears that the magnitude of glacier change is
29 not simply related to dimensional attributes of a given glacier; they apparently vary with
30 differing climatic regimes.

1 Studies have typically found no significant correlation among other morphometric
2 parameters and area change (Paul, 2002; Granshaw and Fountain, 2006; Andreassen et
3 al., 2008; Bolch et al., 2010; and Paul and Andreassen, 2009). Other parameters include
4 slope, aspect, and median, minimum, and maximum elevation. We, however, find
5 correlation between slope and absolute area in all periods. Slope correlates with relative
6 area change from 1952-1985, and on a net basis from 1952-2005, but not for the latter
7 period 1985-2005 (Table 5). This relation, indicating that the steeper glaciers lost less
8 absolute and relative surface area, may be spurious, however, as slope is highly correlated
9 with glacier surface area and length (e.g., Hoelzle et al., 2003).

10 We also find that median, minimum, and maximum glacier elevations (along with
11 elevation range) correlate with area change, but the strength of these associations is not
12 constant through time (Table 5). A study with a larger sample size is required to assess
13 whether the temporal changes we observed in this study are present for other mountain
14 ranges, and how time-variable glacier dynamics might obscure relations between extent
15 change and glacier geometry.

16 **4.5. Relations to climate**

17 Mean annual and seasonal temperatures increased from 1952-2005, particularly after
18 1985, whereas wintertime precipitation slightly decreased (Figs. 10 and 11). Observed
19 mass and area loss coincided with intervals of increased (decreased) temperatures
20 (precipitation), a finding in agreement with previous studies for glaciers in the Cariboo
21 Mountains (Luckman et al., 1987; Brewis, 2012). Previous studies implicate increases in
22 surface air temperatures as the recent cause for accelerated mass loss of North American
23 glaciers in maritime environments (Rasmussen and Conway, 2004; Arendt et al., 2009).
24 Tennant and Menounos (2013) also suggest that decreases in precipitation contribute to
25 mass loss of the Columbia Icefield of the Canadian Rocky Mountains.

26 There was negligible change in surface temperatures from 1952-1970 to 1971-1986, but
27 following 1985, climate warmed in the Cariboo Mountains (Fig. 10). After 1985,
28 temperatures increased during the ablation season and doubled during the accumulation
29 season.

1 Precipitation consistently decreased over the three periods of analysis for the
2 accumulation season and annually (Fig. 11). Decreased annual precipitation is primarily
3 an accumulation season phenomenon, whereas average ablation season precipitation
4 negligibly changed. Cool accumulation season temperatures from 1971-1985 may have
5 counteracted decreased precipitation, leading to snow accumulation comparable to that of
6 the period 1952-1970. Some, but not all, glaciers thickened and advanced between 1952-
7 1985, a result of both individual glacier hypsometry leading to more retained
8 accumulation, and length and slope angle that led to a more rapid terminus response.

9 ClimateWNA records indicate that wet, cool periods coincide with anomalous low-
10 pressure whereas and dry and warm intervals were associated with high-pressure
11 anomalies (Fig. 12). Others note high-pressure anomalies over northwest North America
12 after the late-1970s with coincident glacier recession and thinning (e.g., Bitz and Battisti,
13 1999; Hodge et al., 1998; Rasmussen and Conway, 2004). Glacier change in the Cariboo
14 Mountains and its relation to broad scale changes in atmospheric circulation broadly
15 accord with these previous studies and importantly, our work expands the spatial domain
16 of these climate anomalies and how they influenced glacier change during the mid-20th to
17 early- 21st centuries.

18 Previous studies suggest that glaciologists need to further examine intra- and inter-
19 regional mass balance variability (Braithwaite, 2002), and conclude that there are no
20 means of making an *a priori* selection of a regionally-representative benchmark glacier
21 (Fountain et al., 2009). The paucity of traditional mass-balance and glacier length change
22 measurements limits assessments of regional representativeness. Widespread use of
23 remotely-sensed imagery to derive glacier extents and surface elevation, however,
24 provides one method to document changes of glacier extent and volume change on
25 decadal timescales. We demonstrate that comprehensive glacier inventories and
26 assessments of decadal area and thickness change can be used to make an informed *a*
27 *priori* selection of a representative subset of glaciers. Regional representativeness will be
28 variable with respect to glacier morphometry, climate and glacier response, however.
29 Selection of benchmark glaciers and representative glacier subsets, as well as testing of
30 the regional representativeness of existing benchmark glaciers (e.g., Fountain et al., 2009)
31 should be based on regional glacier morphometry, recent decadal glacier extent and

1 thickness change, and with respect to varying glacier response in different climatic
2 regimes.

3

4 **5. Conclusions**

5 During the period 1952-2005, glaciers of the Cariboo Mountains receded at a rate of 0.19
6 $\pm 0.05\% \text{ a}^{-1}$. Slow glacier recession rates characterized the epoch 1952-1985 ($-0.05 \pm$
7 $0.10\% \text{ a}^{-1}$), and some glaciers advanced. After 1985, glacier recession rates increased
8 eightfold ($0.41 \pm 0.12\% \text{ a}^{-1}$). Thinning rates also accelerated from $-0.143 \pm 0.043 \text{ m w.e. a}^{-1}$
9 1 (1952-1985) to $-0.500 \pm 0.070 \text{ m w.e. a}^{-1}$ from 1985-2005. Temperatures increased from
10 1952-2005, primarily after 1985, whereas accumulation season precipitation decreased
11 over the period of study, indicating that both increases in temperature and decreases in
12 precipitation played important roles in forcing the observed pattern of glacier change.

13 The inventory of Bolch et al. (2010) marginally overestimated the recession of Cariboo
14 Mountains glaciers from 1985-2005. For 28 common glaciers, our extents average 2%
15 smaller than the 2005 extents generated with the semi-automated method of Bolch et al.
16 (2010) and 5% smaller than the 1985 extents of the TRIM dataset, likely due to mapping
17 of late-lying seasonal snow as glacierized area in the TRIM dataset. When uncertainties
18 are taken into account, however, the average difference between our subset and that of
19 Bolch et al. (2010) is not significant.

20 Our results indicate that relations between glacier change and dimensional attributes of
21 the glaciers of this study are not stable through time; this non-stationarity may be related
22 to ice dynamics and the complex way glaciers respond to changes in surface mass
23 balance.

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7

1 **References**

- 2 Abermann, J., Lambrecht, A., Fischer, A., and Kuhn, M.: Quantifying changes and
3 trends in glacier area and volume in the Austrian Ötztal Alps (1969-1997-2006), *The*
4 *Cryosphere*, 3, 205-215, 2009.
- 5 Andreassen, L. M., Paul, F., Kääb, A., and Hausberg, J. E.: Landsat-derived glacier
6 inventory for Jotunheimen, Norway, and deduced glacier changes since the 1930s, *The*
7 *Cryosphere*, 2, 131-145, 2008.
- 8 Arendt, A. A., Echelmeyer, K. A., Harrison, W. D., Lingle, C. S., and Valentine, V. B.:
9 Rapid wastage of Alaska glaciers and their contribution to rising sea level, *Science*, 297,
10 382-385, 2002.
- 11 Arendt, A., Echelmeyer, K., Harrison, W., Lingle, C., Zirnheld, S., Valentine, V., Ritchie,
12 B., and Druckenmiller, M.: Updated estimates of glacier volume changes in the western
13 Chugach Mountains, Alaska, and a comparison of regional extrapolation methods, *J.*
14 *Geophys. Res.*, 111, F03019, doi:10.1029/2005JF000436, 2006.
- 15 Arendt, A., Walsh, J., and Harrison, W.: Changes of glaciers and climate in
16 northwestern North America during the late 20th century, *J. Climate*, 22, 4117-4134,
17 2009.
- 18 Bahr, D. B., and Radić, V.: Significant contribution to total mass from very small
19 glaciers, *The Cryosphere*, 6, 763-770, doi:10.5194/tc-6-763-2012, 2012.
- 20 Barrand, N. E., Murray, T., James, T. D., Barr, S. L., and Mills, J. P.: Optimizing
21 photogrammetric DEMs for glacier volume change assessment using laser-scanning
22 derived ground-control points, *J. Glaciol.*, 55, 106-116, 2009.
- 23 Barrand, N. E., James, T. D., and Murray, T.: Spatio-temporal variability in elevation
24 changes of two high-Arctic valley glaciers, *J. Glaciol.*, 56, 771-780, 2010.
- 25 Beedle, M. J., Menounos, B., Luckman, B. H., and Wheate, R.: Annual push moraines as
26 climate proxy, *Geophys. Res. Lett.*, 36, L20501, doi:10.1029/2009GL039533, 2009.

1 Beedle, M. J., Menounos, B., and Wheate, R.: An evaluation of mass balance techniques
2 applied to Castle Creek Glacier, British Columbia, Canada, *J. Glaciol.*, 60, 262-276,
3 2014.

4 Berthier, E., Schiefer, E., Clarke, G. K. C., Menounos, B., and Rémy, F.: Contribution of
5 Alaskan glaciers to sea-level rise derived from satellite imagery, *Nat. Geosci.*,
6 doi:10.1038/NGEO737, 2010.

7 Bitz, C. M., and Battisti, D. S.: Interannual to decadal variability in climate and the
8 glacier mass balance in Washington, western Canada, and Alaska, *J. Climate*, 12, 3181-
9 3196, 1999.

10 Bogdal, C., Schmid, P., Zennegg, M., Anselmetti, F. S., Scheringer, M., and
11 Hunberbühler, K.: Blast from the past: melting glaciers as a relevant source for persistent
12 organic pollutants, *Environ. Sci. Technol.*, 43, 21, 8173-8177, 2009

13 Bolch, T., Menounos, B., and Wheate, R.: Landsat-based inventory of glaciers in western
14 Canada, 1985-2005, *Remote Sens. Environ.*, 114, 127-137, 2010.

15 Braithwaite, R. J.: Glacier mass balance: the first 50 years of international monitoring,
16 *Prog. Phys. Geog.*, 26, 76-95, 2002.

17 Brewis, T. B.: Glacier change and contribution to streamflow in the Canoe Basin, British
18 Columbia, 1948-2005 (Master's Thesis). University of Northern British Columbia, 2012.

19 British Columbia (BC) Ministry of Environment: Specifications for aerial triangulation.
20 Surveys and Resource Mapping, Province of British Columbia, Victoria, BC, 1998.

21 Daly, C., Gibson, W. P., Taylor, G. H., Johnson, G. L., and Pasteris, P.: A knowledge-
22 based approach to the statistical mapping of climate, *Climate Res.*, 22, 99-113, 2002.

23 DeBeer, C. M., and Sharp, M. J.: Recent changes in glacier area and volume within the
24 southern Canadian Cordillera, *Ann. Glaciol.*, 46, 215-221, 2007.

1 DeBeer, C. M., and Sharp, M. J.: Topographic influences on recent changes of very small
2 glaciers in the Monashee Mountains, British Columbia, Canada, *J. Glaciol.*, 55, 1-10,
3 2009.

4 Déry, S. J., Clifton, A., MacLeod, S. and Beedle, M. J.: Blowing snow fluxes in the
5 Cariboo Mountains of British Columbia, Canada. *Arct. Antarct. Alp. Res.*, 42, 2, 188-
6 197, doi: 10.1657/1938-4246-42.2.188, 2010.

7 Environment Canada: 1981-2010 Climate Normals & Averages. Meteorological Service
8 of Canada, Environment Canada, http://climate.weather.gc.ca/climate_normals/), 2012.

9 Fountain, A. G., Hoffman, M. J., Granshaw, F., and Riedel, J.: The ‘benchmark glacier’
10 concept – does it work? Lessons from the North Cascade Range, USA, *Ann. Glaciol.*, 50,
11 163-168, 2009.

12 Gardner, A. S., Moholdt, G., Wouters, B., Wolken, G. J., Burgess, D. O., Sharp, M. J.,
13 Cogley, J. G., Braun, C., and Labine, C.: Sharply increased mass loss from glaciers and
14 ice caps in the Canadian Arctic Archipelago, *Nature*, 473, 357-360,
15 doi:10.1038/nature10089, 2011.

16 Granshaw, F. D., and Fountain, A. G.: Glacier change (1958-1998) in the North Cascades
17 National Park Complex, Washington, USA, *J. Glaciol.*, 52, 251-256, 2006.

18 Hodge, S. M., Trabant, D. C., Krimmel, R. M., Heinrichs, T. A., March, R. S., and
19 Josberger, E. G.: Climate variations and changes in mass of three glaciers in western
20 North America, *J. Climate*, 11, 2161-2179, 1998.

21 Hoelzle, M., Haeberli, W., Dischl, M., and Peschke, W.: Secular glacier mass balances
22 derived from cumulative glacier length changes, *Global Planet. Change*, 36, 295-306,
23 2003.

24 Hood, E., Fellman, J., Spencer, R. G. M., Hernes, P. J., Edwards, R., D’Amore, D., and
25 Scott, D.: Glaciers as a source of ancient and labile organic matter to the marine
26 environment, *Nature*, 462, doi:10.1038/nature08580, 2009.

1 Huss, M.: Density assumptions for converting geodetic glacier volume change to mass
2 change, *The Cryosphere*, 7, 877-887, doi:10.5194/tc-7-877-2013, 2013.

3 Jiskoot, H., Curran, C. J., Tessler, D. L., and Shenton, L. R.: Changes in Clemenceau
4 Icefield and Chaba Group glaciers, Canada, related to hypsometry, tributary detachment,
5 length-slope and area-aspect relations, *Ann. Glaciol.*, 50, 133-143, 2009.

6 Kääb, A., Paul, F., Maisch, M., Hoelzle, M., and Haeberli, W.: The new remote sensing
7 derived Swiss glacier inventory: II. First results, *Ann. Glaciol.*, 34, 362-366, 2001.

8 Kääb, A., and Vollmer, M.: Surface geometry, thickness changes and flow fields on
9 creeping mountain permafrost: automatic extraction by digital image analysis. *Permafrost*
10 *Periglac.*, 11, 315-326, 2000.

11 Kalnay, E. M., Kanamitsu, R., Kistler, W., Collins, W., Deaven, D., Gandin, L., Iredell,
12 M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W.,
13 Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Jenne, R., and Joseph,
14 D.: The NCEP/NCAR 40-year reanalysis project. *B. Am. Meteorol. Soc.*, 77, 3, 437-471,
15 1996.

16 Koblet, T., Gärtner-Roer, I., Zemp, M., Jansson, P., Thee, P., Haeberli, W., and
17 Holmlund, P.: Reanalysis of multi-temporal aerial images of Storglaciären, Sweden
18 (1959-99) – Part 1: Determination of length, area and volume changes, *The Cryosphere*,
19 4, 333-343, doi:10.5194/tc-4-333-2010, 2010.

20 Koch, J., Menounos, B., and Clague, J. J.: Glacier change in Garibaldi Provincial Park,
21 southern Coast Mountains, British Columbia, since the Little Ice Age, *Global Planet.*
22 *Change*, 66, 161-178, 2009.

23 Luckman, B. H., Harding, K. A., and Hamilton, J. P.: Recent glacier advances in the
24 Premier Range, British Columbia, *Can. J. Earth Sci.*, 24, 1149-1161, 1987.

25 Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M. and Francis, R. C.: A Pacific
26 interdecadal climate oscillation with impacts on salmon production. *B. Am. Meteorol.*
27 *Soc.*, 78, 1069-1079, 1997.

- 1 Marshall, S. J., White, E. C., Demuth, M. N., Bolch, T., Wheate, R., Menounos, B.,
2 Beedle, M. J., and Shea, J. M.: Glacier water resources on the eastern slopes of the
3 Canadian Rocky Mountains, *Can. Water Resour. J.*, 36, 2, 109-134, 2011.
- 4 Maurer, M. K., Menounos, B., Luckman, B. H., Osborn, G., Clague, J. J., Beedle, M. J.,
5 Smith, R., and Atkinson, N.: Late Holocene glacier expansion in the Cariboo and
6 northern Rocky Mountains, British Columbia, Canada, *Quaternary Sci. Rev.*, 51, 71-80,
7 2012.
- 8 Menounos, B., Osborn, G., Clague, J., and Luckman, B.: Latest Pleistocene and Holocene
9 glacier fluctuations in western Canada, *Quaternary Sci. Rev.*, 28, 2049-2074, 2009.
- 10 Mitchell, T. D., and Jones, P. D.: An improved method of constructing a database of
11 monthly climate observations and associated high-resolution grids, *Int. J. Climatol.*, 25,
12 693-712, 2005.
- 13 Moore, R. D., Fleming, S. W., Menounos, B., Wheate, R., Fountain, A., Stahl, K., Holm,
14 K., and Jakob, M.: Glacier change in western North America: influences on hydrology,
15 geomorphic hazards and water quality, *Hydrol. Process.*, 24, 42-61, 2009.
- 16 Paul, F.: Changes in glacier area in Tyrol, Austria, between 1969 and 1992 derived from
17 Landsat 5 Thematic Mapper and Austrian Glacier Inventory data, *Int. J. Remote Sensing*,
18 23, 787-799, 2002.
- 19 Paul, F., and Andreassen, L M.: A new glacier inventory for the Svartisen region,
20 Norway, from Landsat ETM+ data: challenges and change assessment, *J. Glaciol.*, 55,
21 607-618, 2009.
- 22 Paul, F., and Haeberli, W.: Spatial variability of glacier elevation changes in the Swiss
23 Alps obtained from two digital elevation models, *Geophys. Res. Lett.*, 35,
24 doi:10.1029/2008GL034718, 2008.
- 25 Paul, F., Kääb, A., Maisch, M., Kellenberger, T., and Haeberli, W.: Rapid disintegration
26 of Alpine glaciers observed with satellite data, *Geophys. Res. Lett.*, 31, L21402,
27 doi:10.1029/2004GL020816, 2004.

- 1 Radić, V. and Hock, R.: Regionally differentiated contribution of mountain glaciers and
2 ice caps to future sea-level rise, *Nat. Geosci.*, 4, 91-94, doi:10.1038/NGEO1052, 2011.
- 3 Rasmussen, L. A., and Conway, H.: Climate and glacier variability in western North
4 America, *J. Climate*, 17, 1804-1815, 2004.
- 5 Rolstad, C., Haug, T., and Denby, B.: Spatially integrated geodetic glacier mass balance
6 and its uncertainty based on geostatistical analysis: application to the western Svartisen
7 ice cap, *J. Glaciol.*, 55, 666-680, 2009.
- 8 Sapiano, J. J., Harrison, W. D., and Echelmeyer, K. A.: Elevation, volume and terminus
9 changes in nine glaciers in North America, *J. Glaciol.*, 44, 119-135, 1998.
- 10 Schiefer, E., and Gilbert, R.: Reconstructing morphometric change in a proglacial
11 landscape using historical aerial photography and automated DEM generation,
12 *Geomorphology*, 88, 167-178, 2007.
- 13 Schiefer, E., Menounos, B., and Wheate, R.: Recent volume loss of British Columbia
14 glaciers, Canada, *Geophys. Res. Lett.*, 34, L16503, doi:10.1029/2007GL030780, 2007.
- 15 Serandbrei-Barbero, R., Rabagliati, R., Binaghi, E., and Rampini, A.: Glacial retreat in
16 the 1980s in the Breonie, Aurine and Pusteresi groups (eastern Alps, Italy) in Landsat TM
17 images, *Hydrological Sciences*, 44, 279-296, 1999.
- 18 Tennant, C., Menounos, B., Wheate, R., and Clague, J. J.: Area change of glaciers in the
19 Canadian Rocky mountains, 1919 to 2006, *The Cryosphere*, 6, 1541-1552,
20 doi:10.5194/tc-6-1541-2012, 2012.
- 21 Tennant, C., and Menounos, B.: Glacier change of the Columbia Icefield, Canadian
22 Rocky Mountains, 1919-2009, *J. Glaciol.* 59, 671-686, doi: 10.3189/2013JoG12J135,
23 2013.
- 24 Wang, T., Hamann, A., Spittlehouse, D., and Murdock, T. N.: ClimateWNA – High-
25 resolution spatial climate data for western North America, *J. Appl. Meteorol. Clim.*, 61,
26 16-29, 2012.

- 1 Figure 1. Study area: the three red rectangles indicate subregions in this study (Castle,
- 2 Quanstrom, and Premier) and the location of the three maps in Figure 2.