



Landsat-based inventory of glaciers in western Canada, 1985–2005

Tobias Bolch*, Brian Menounos, Roger Wheate

Natural Resources and Environmental Studies Institute, University of Northern British Columbia, 3333 University Way, Prince George, British Columbia Canada V2N 4Z9

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ABSTRACT

We report on a glacier inventory for the Canadian Cordillera south of 60°N, across the two western provinces of British Columbia and Alberta, containing ~30,000 km² of glacierized terrain. Our semi-automated method extracted glacier extents from Landsat Thematic Mapper (TM) scenes for 2005 and 2000 using a band ratio (TM3/TM5). We compared these extents with glacier cover for the mid-1980s from high-altitude, aerial photography for British Columbia and from Landsat TM imagery for Alberta. A 25 m digital elevation model (DEM) helped to identify debris-covered ice and to split the glaciers into their respective drainage basins. The estimated mapping errors are 3–4% and arise primarily from seasonal snow cover. Glaciers in British Columbia and Alberta respectively lost $-10.8 \pm 3.8\%$ and $-25.4 \pm 4.1\%$ of their area over the period 1985–2005. The region-wide annual shrinkage rate of $-0.55\% \text{ a}^{-1}$ is comparable to rates reported for other mountain ranges in the late twentieth century. Least glacierized mountain ranges with smaller glaciers lost the largest fraction of ice cover: the highest relative ice loss in British Columbia ($-24.0 \pm 4.6\%$) occurred in the northern Interior Ranges, while glaciers in the northern Coast Mountains declined least ($-7.7 \pm 3.4\%$).

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1. Introduction

Surface runoff from snowmelt and glaciers is an essential freshwater resource in western North America, especially during summer when the water demand is high (Barnett et al., 2005; Stahl and Moore, 2006). In western Canada glacier runoff is a vital component of surface flows to drainage basins of the eastern Rocky Mountains where runoff is used for agriculture, urban consumption, and industry. Hydroelectric power generation also relies on glacier runoff in glacierized basins of British Columbia (Moore et al., 2009). Finally, decline in glacier extent in western Canada and Alaska significantly contributes to sea level rise (Arendt et al., 2002; Larsen et al., 2007; Schiefer et al., 2007).

The first attempt to inventory glaciers in western Canada used extents from 1:1,000,000 scale maps (Falconer et al., 1966). Later, the Glacier Inventory of Canada aimed to catalogue all glaciers at a scale of 1:500,000 as part of Canada's contribution to the International Hydrological Decade (1965–1974), but was never completed (Ommanney, 1980, 2002b). Pilot studies for the World Glacier Inventory catalogued limited regions of the Canadian Cordillera (Ommanney, 1971; Stanley, 1970). Only the glaciers on Vancouver Island and small regions of the Rocky and Coast mountains are included in the World Glacier Inventory (WGI, <http://nsidc.org/data/g01130.html>). Results from these early glacier inventories are

summarized by Haeberli et al. (1989) and Ommanney (2002b). Direct measurements of mass balance exist for only a few glaciers in Western Canada (Moore et al., 2009). Those data show a consistent pattern: slight positive mass balances in the mid 1970s, 1 or 2 years of positive mass balance at the end of the 1990s, and otherwise strong negative mass balance (WGMS, 2007).

There have been recent efforts to document the area and volume loss of glaciers in western Canada, but none of these studies inventories all glaciers in British Columbia and Alberta (DeBeer and Sharp, 2007; Demuth et al., 2008; Larsen et al., 2007; VanLooy and Forster, 2008). Schiefer et al. (2008) presented a glacier inventory for glaciers of British Columbia based on extents obtained from aerial photography in the 1980s. However, their analysis included neither glaciers in Alberta nor more recent extents and changes in glacier cover.

We expand on the work of Schiefer et al. (2008) and report on the approach to generate a glacier inventory from satellite imagery for the year 2005 for British Columbia and Alberta, Canada within the time frame of less than 1 year. We compare these results to earlier extents derived from aerial photography to report on area loss over this 20 year period. We further utilize satellite imagery from the year 2000 for 50% of our study area to extend the temporal coverage of our analysis. The inventory data generated are available through the Global Land Ice Measurements from Space (GLIMS) database (Bolch et al., 2008b).

2. Study area and glaciers in western Canada

Our study focuses on glaciers in the Canadian Cordillera south of 60°N, a broad, mountainous region covering roughly 1,000,000 km² that can be subdivided into Western, Interior and Eastern mountain

* Corresponding author. Current address: Institut für Kartographie, Technische Universität Dresden, 01062 Dresden, Germany.

E-mail address: tobias.bolch@tu-dresden.de (T. Bolch).

systems. The Insular, Coast, and St. Elias mountains encompass the Western System. The Interior System in the south contains the Purcell, Selkirk, Cariboo, and Monashee mountains between 119–115°W longitude and 49–54°N latitude. The Interior Plateau divides mountains of the southern Interior from their counterparts in the north: the Hazelton, Skeena, Cassiar, and Omineca mountains. The Eastern System is defined by the Rocky Mountains that continue north from the US and terminate south of the Liard River. Local relief typically exceeds 600 m for many of these ranges, and some of the highest peaks in the Rocky, St. Elias, and Coast mountains exceed 4000 m above sea level (m a.s.l.). We subdivide the mountains into nine regions based on natural boundaries (Fig. 1). Similar climate and glacier characteristics typify these regions, and they conform to the regions presented by Schiefer et al. (2007).

Located in the zone of mid-latitude Westerlies, strong precipitation gradients are common in the study area with total precipitation declining from west to east. Maximum precipitation occurs in the Coast Mountains during the winter months due to cyclonic activities, while summer precipitation is predominant in the Rocky Mountains (Barry, 2008). Local- to regional-scale precipitation patterns are heavily influenced by topographic factors, which in turn impact glacier mass balance (Letréguilly, 1988; Shea et al., 2004).

Glaciers occupied about 30,000 km² in the 1980s in British Columbia and Alberta based on provincial and federal mapping data; this estimate of glacier extent represents about 23% of the North American and 4% of the world's non-polar ice coverage (Schiefer et al., 2007; Williams and Ferrigno, 2002). Glacier types in the Canadian Cordillera range from large ice fields to valley and small hanging

glaciers (Schiefer et al., 2008). Debris covers the ablation zone of some large glaciers in many mountain ranges (Ommanney, 2002a), and rock glaciers occur in continental sites. Rock glaciers, however, are not inventoried in the present study. The mean glacier elevation can be lower than 1250 m a.s.l. in the northern Coast Mountains but often exceeds 2750 m a.s.l. in the southern Rocky Mountains (Schiefer et al., 2007, 2008). The predominant aspect of the upper glacier areas is north and north-east (Schiefer et al., 2008).

3. Methods and data

3.1. Glacier mapping: previous applications

Semi-automated multispectral glacier mapping methods include supervised classification (Aniya et al., 1996; Gratton et al., 1990; Sidjak and Wheate, 1999), thresholding of ratio images (Paul et al., 2002; Rott, 1994) and the Normalised Difference Snow Index (NDSI) (Hall et al., 1995; Racoviteanu et al., 2008). Thresholding of ratio images is a robust and time effective approach compared to manual digitization and also enables identification of snow and ice in shadow (Paul and Kääb, 2005; Paul et al., 2003; Bolch and Kamp, 2006). The RED/SWIR ratio (e.g. TM3/TM5) has the advantage over the NIR/SWIR ratio (e.g. TM4/TM5) in that it works better in shadows and with thin debris-cover (Andreassen et al., 2008; Paul and Kääb, 2005). However, this ratio method suffers from two primary limitations: the recorded ratio of reflection of water bodies is similar to snow and ice, and in common with other automated methods based on multispectral data, areas of debris-covered ice are not

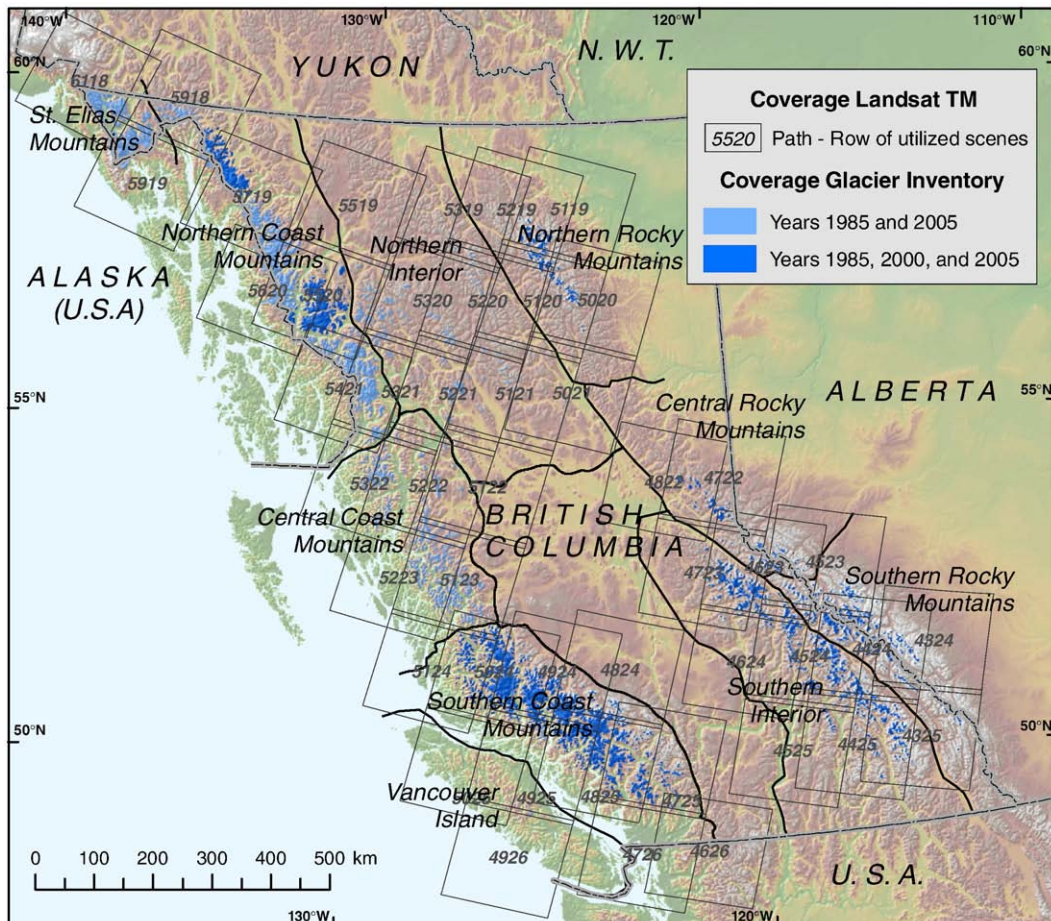


Fig. 1. Study area showing the sub-regions, path and row of the utilized Landsat scenes, and the coverage of the glacier inventory.

distinguished due to the spectral similarity with surrounding bedrock (Bolch et al., 2008a).

In general, water bodies are detectable using the Normalised Difference Water Index (NDWI), but turbid lakes and areas in cast shadow are problematic (Huggel et al., 2002). We tested the NDWI method for the northern Rocky Mountains and encountered the same problems. We found that manual editing of the glacier polygons to exclude misclassified water bodies was superior to any automated method and involved less time. Promising approaches to map debris-covered glaciers include those based on thermal information (Ranzi et al., 2004), a slope threshold in combination with neighbourhood analysis and change detection (Paul et al., 2004a), morphometric analysis (Bishop et al., 2001; Bolch and Kamp, 2006) or a combination of thermal information and morphometric parameters (Bolch et al., 2007). However, these methods suffer from high errors (>5%) requiring editing during post processing, a DEM of sufficient accuracy and only successfully operate on small regions where the methodology can be optimized.

3.2. Data

The British Columbia Government produced glacier extents and a 25-m digital elevation model (DEM) under the Terrain Resource Inventory Management (TRIM) program at a scale of 1:20,000. TRIM was based on aerial photography mostly acquired during late summer 1982–1988 (Geographic Data British Columbia, <http://ilmbwww.gov.bc.ca/bmgs/pba/trim>). We generated a 25 m DEM for western Alberta from mass points with a spacing varying from 25 m and up to 80 m in the Banff and Jasper national parks, and breaklines using a TIN algorithm. The TIN was then converted into a grid with a resolution of 25 m to match the TRIM DEM.

The (median date) 1985 glacier inventory for British Columbia uses the polygons from TRIM (Schiefer et al., 2007). Glacier extents for Alberta from the Canadian National Topographic DataBase (NTDB) were available, but are mainly from 1994 and contain large discrepancies between glacier polygons and glaciers revealed in satellite imagery from similar acquisition years (e.g. glaciers are mapped where no snow and ice can be identified on the imagery).

Our glacier inventory employed orthorectified Landsat imagery as a compromise between the large field of view (180 × 170 km) and spatial resolution (30 m). The British Columbia Ministry of Forests and Range provided Landsat 5 TM imagery from 2003–2007, rectified to better than ± 15 m root mean squared error (RMSE). We selected 41 scenes from the years 2004 to 2006 for the 2005 inventory and two scenes acquired in 2003 and 2007 (Appendix A and Bolch et al., 2008b). Landsat coverage with no clouds and minimal seasonal snow was available for all regions, and most of the selected scenes were acquired in late summer.

We also used orthorectified Landsat images (L1G) from the Global Land Cover Facility (GLCF: <http://www.landcover.org>) and purchased other scenes to map the 1985 glacier extents in Alberta, demarcate glacier extents in 2000 for selected regions, and evaluate glacier polygons from the TRIM program. The reported positional accuracy of the orthorectified GLCF scenes is ± 50 m (Tucker et al., 2004), and visual inspection indicated a good fit with the TRIM glacier outlines. However, we commonly observed a shift of 15 m, and a maximum shift of 60 m occurred near the uppermost areas of steep terrain. As a consequence of these positional errors and seasonal snow on some of the GLCF scenes from 2000, we could not successfully identify all small, high-altitude glaciers. Orthorectification of the purchased scenes produced root mean square errors (RMSE) of less than 30 m. Reported horizontal and vertical errors of the DEM are ± 10 and ± 5 m, respectively (British Columbia Ministry of Environment, Land and Parks, 1992). However, higher vertical errors and artefacts such as striping occur in the accumulation areas of some glaciers due to poor contrast in the aerial photography (Schiefer et al., 2007; VanLooy and Forster, 2008).

3.3. Glacier identification

3.3.1. Glacier outlines of 1985 for British Columbia

Our 1985 inventory for British Columbia uses glacier polygons from the provincial TRIM program. In some cases, however, these polygons contain substantial errors that stem from interpretation errors, presence of debris cover, and seasonal snow. Debris-covered ice, for example, was often incorrectly mapped on large glacier tongues. These mapping errors were identified based on the unrealistic shape of mapped glacier termini and through comparison with satellite imagery. Additional information was provided by the hillshaded TRIM-DEM (sun elevation angle: 45°, azimuth: 315°). We also utilized in a few instances morphometric parameters such as slope, plan and profile curvature to help identify landforms (Schmidt and Dikau, 1999), as marked concavity can represent the transition of the glaciers to surrounding moraines or forefield (Bolch and Kamp 2006). The identification of errors due to seasonal snow cover, especially for small glaciers presented a greater challenge than debris-cover. We used qualitative measures such as irregular glacier shapes or large deviations between glacier areas in 1985 and 2005 to identify glaciers that required further scrutiny. We manually improved those erroneous polygons via Landsat TM scenes from approximately the same year.

3.3.2. Glacier outlines of 2005

We selected the TM3/TM5 band ratio for glacier mapping based on previous experience and tests that we completed for glaciers in the northern Rocky Mountains and Interior Ranges (discussed below). For the entire study area, we used our improved British Columbia TRIM glacier outlines as a mask to minimize misclassification due to factors such as seasonal snow. When using this mask, we assumed that glaciers did not advance between 1985 and 2005, an assumption that holds for practically all non-tidewater glaciers in western North America (Moore et al., 2009). The mask also maintained consistency in the location of the upper glacier boundary and the margins of nunataks. This consistency is important in case of seasonal snow that hampers correct identification of the upper glacier boundary. In addition, all snow and ice patches that were not considered to be perennial ice in the TRIM data were eliminated and hence, we minimize deviations in glacier areas that could arise from interpretative errors or major variations in snow cover (e.g. Paul and Andreassen, 2009).

We mapped only glaciers larger than 0.05 km² as a smaller threshold would include many features that were most likely snow patches. We could not justify the costs in terms of effort and high relative error to map glaciers at a larger scale, especially given the spatial extent of our study. We identified internal single pixel 'holes' in the glacier polygons based on an area threshold and deleted them as these are usually misclassified pixels due to glacier debris. The resulting glacier polygons were visually checked for gross errors based on the procedures previously discussed, and overall, less than 5% of the glaciers were manually improved.

3.3.3. Glacier outlines of 1985 for Alberta and of 2000 for selected areas

We generated the mid-1980s glacier extents for Alberta from Landsat TM scenes using the same method as described in the previous section. As no glacier polygons from earlier dates were available as a mask, we used the area threshold of 0.05 km² and the Normalised Difference Vegetation Index (NDVI) to reduce misclassified pixels. Nevertheless, substantially more time and effort was required to generate these extents for Alberta than editing the available mid-1980s glacier extents for a comparable area in British Columbia.

We also generated glacier outlines for 2000 for selected representative regions in our study: the southern Coast Mountains, the southern Interior Ranges, the southern Rocky Mountains, the northern Rocky

Mountains and a portion of the northern Coast Mountains (Fig. 1). While larger glaciers could be correctly delineated, it was difficult to distinguish small areas of high elevation glacier ice from surrounding snow in several regions, due to remaining seasonal snow cover. For this dataset, more than 5% of the polygons had to be manually corrected and the overall workload was similar to the 2005 inventory due to more manual effort although fewer polygons had to be checked.

3.3.4. Glacier drainage basins

We derived glacier drainage basins using the DEM and a buffer around each glacier (Fig. 2); this approach can be used for any time period and extents, in contrast to methods linked to specific glacier outlets, and thus to a morphology for a given period of time (Manley, 2008; Schiefer et al., 2008). The optimum buffer size varied according to glacier size and the investigated time period: for this study, it varied from 1 to 1.5 km. Our method assumes no migration of flow divides through time. After identifying the optimum buffer size for each region, the DEM was clipped to this buffer. The next step was the calculation of glacier basins by hydrological analysis. The pour points are the lowermost points at the edge of the clipped DEM. We subsequently converted the calculated basin grid into polygons which represent glacier drainage basins and these polygons were used to clip the glaciers. These basins do not necessarily contain only one glacier, but could also contain several smaller glaciers. However, subsequent

change analysis is based on each glacier. The main errors of this approach are due to DEM artefacts in the accumulation zones (Fig. 3) and also where small glaciers without a distinctive tongue could not be separated from adjacent, larger glaciers. We manually improved gross errors with the help of the shaded relief data and the Landsat scenes. Where small parts of glaciers reached over a mountain ridge, we treated these hydrologically distinct ice bodies as separate glaciers if they exceeded 0.05 km². Smaller snow and ice polygons were omitted, and the omitted area was less than 0.3%.

3.3.5. Glacier inventory, glacier parameters, and change analysis

Where glaciers extend across the borders with Alaska (USA) and Yukon Territory (Canada), we included them in both 1985 and 2005 inventories if the greater part of the glacier is in British Columbia and if we had access to suitable Landsat imagery for both dates. Our criteria excluded ca. 660 km² ice covered area in British Columbia, but it included about 1400 km² of ice in Alaska and 100 km² in Yukon Territory.

We used the GLIMS identification system based on glacier coordinates (Raup and Khalsa, 2007). However, we introduced a prefix that represents the hydrological basin system following the official numbering of the Water Survey of Canada (<http://www.wsc.ec.gc.ca>). Characteristic parameters (area, elevation, slope, aspect) for each glacier were obtained from the 25 m DEM. The final database includes the following: WC2N_ID, GLIMS_ID, name (if existing), province, region,

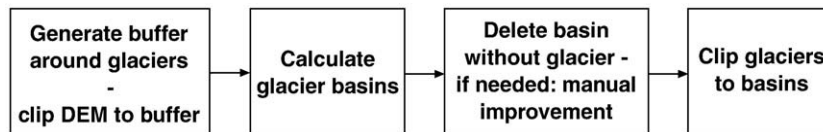


Fig. 2. Flow chart showing the process of deriving the glacier drainage basins.

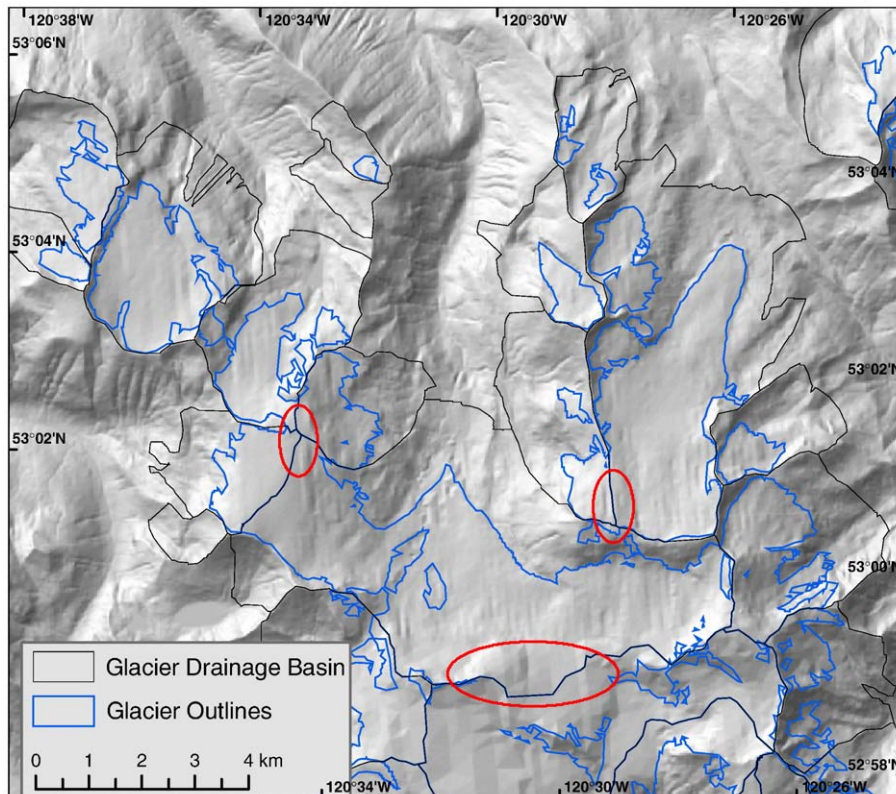


Fig. 3. Sample of delineated glacier drainage basins. Red ellipses indicate examples of uncertain ice divides due to the erroneous DEM in the accumulation zones.

Table 1

Comparison of the outlines of the 2005 glacier inventory and independently digitized outlines based on aerial photography of the same year (Matt Beedle, pers. comm. 2007).

Glacier/Icefield (Region)	Area ^a [km ²]	Area ^b [km ²]	Deviation [km ²]	Deviation [%]
Castle Creek Glacier (Southern Interior)	9.66	9.90	+0.24	+2.4
Lloyd George Ice Field (Northern Rocky Mountains)	48.27	49.02	+0.75	+1.5
Peyto Glacier (Southern Rocky Mountains)	10.69	10.51	-0.18	-1.7

Debris-cover was manually corrected for Peyto Glacier and one glacier at Lloyd George Icefield.

^a From aerial photography.

^b Satellite imagery.

source time, area, minimum, maximum, median, and mean elevation, mean slope and aspect. We calculated these glacier attributes in a GIS and used sines and cosines to determine aspect (Schiefer et al., 2008). Subsequent change analysis was based on the glacier extents of 1985 and their identification number because some glaciers disintegrated and new IDs had to be added for the 2000 and 2005 inventories.

3.3.6. Error estimation

Sources of potential error in area estimates include the following factors:

a) *Method of glacier delineation (e_a)*: Previous studies using a band ratio method to map glaciers indicate an error of ca. ±2% for debris-free glaciers (Bolch and Kamp, 2006; Paul et al., 2003). Our tests based on comparison with independently generated outlines from aerial photography confirm the magnitude of this error term

for the present study (Table 1, Fig. 4). The margins of debris-covered glaciers were manually improved, but due to the size of the study area and the number of glaciers, some smaller debris-covered glaciers may not have been identified. An additional error of ±0.5% was added to account for the more difficult delineation of debris-covered glacier tongues. This error term is based on random tests over the study area where we compared the improved glacier outlines based on the Landsat data with higher resolution aerial photos. Hence, we estimate the mapping error to be ±2.5%.

b) *Error in co-registration and glacier size (e_b)*: Visual checks confirmed the accuracy of the 2005 co-registered imagery and mean deviation was within ±15 m, compared to the given ±50 m for the 2000 GLCF imagery. We estimate this error term based on a buffer for each glacier similar to the method suggested by Granshaw and Fountain (2006). The buffer size was chosen to be half of the estimated shift caused by misregistration as only one side can be affected by the shift and the resulting cut off by the TRIM outlines. This method includes the relative higher error of small polygons as a small glacier has relatively more edge pixels.

c) *Scene quality, clouds, seasonal snow, and shadow (e_c)*: Seasonal snow introduced errors in area determination of small, high altitude glaciers, but there were negligible errors from clouds and shadows. We estimate an error of ±3% for scenes that have late-lying snow, based on tests, where we visually compared automated derived outlines with manually improved ones, conducted on TM scenes across the study area. This error was added to each study area based on the fraction of scenes with seasonal snow. For example, the two scenes covering the northern Rocky Mountains had no seasonal snow, hence no error term was applied, whereas four of the six scenes of the central Coast Mountains were affected by seasonal snow, and an error ±2% was added.

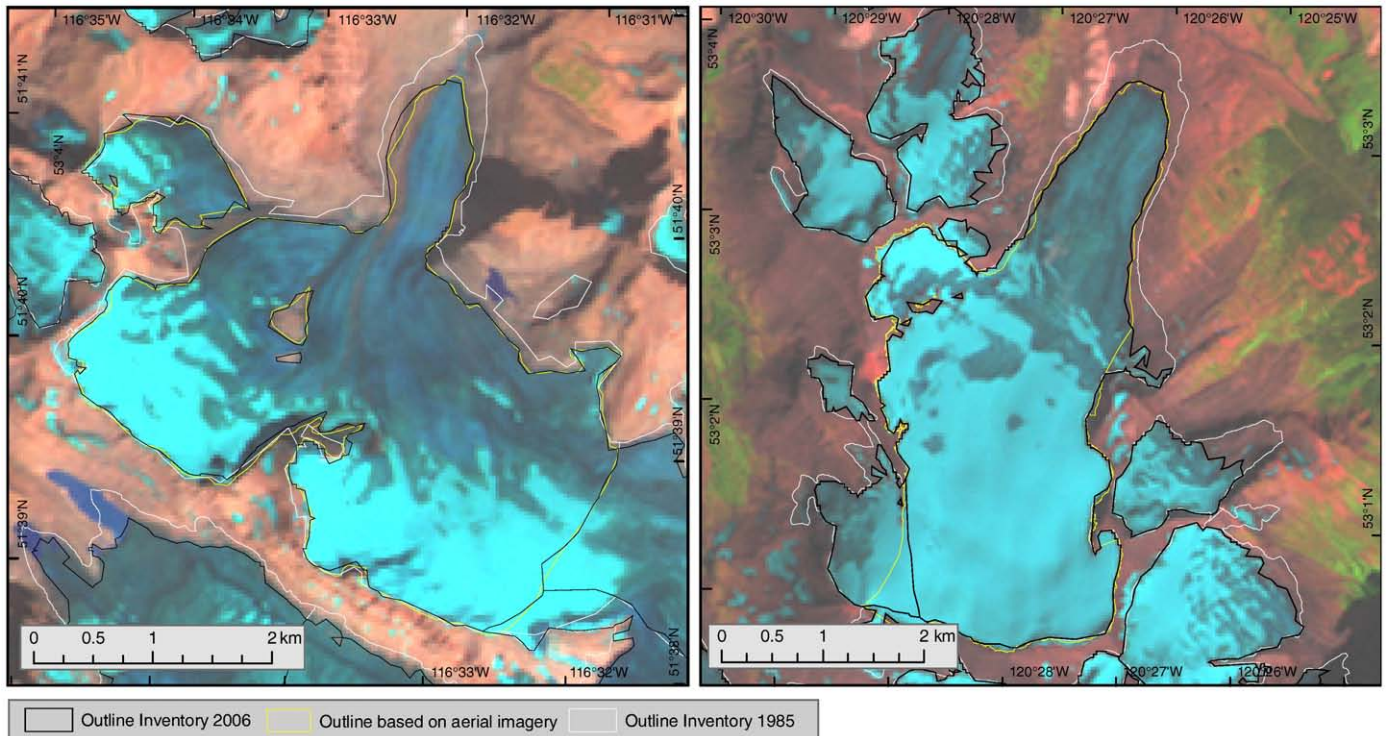


Fig. 4. Deviation of glacier outlines digitized manually from high resolution aerial photography (Matt Beedle, pers comm., 2007) and derived from Landsat TM data using our automated approach; left: Peyto Glacier in the southern Rocky Mountains, right: Castle Creek Glacier in the southern Interior Ranges; the arrows indicate problematic areas: A: Drainage basin delineation, B: Different interpretation of snow cover, C: Internal rocks, D: Debris-cover.

The total error is thus estimated as the root sum square of each error term.

4. Results

4.1. Errors in TRIM outlines

Errors in the original TRIM glacier outlines occur in all regions, but glacier extent was significantly overestimated due to seasonal snow in three regions: Vancouver Island (TRIM data, original: 28.8 km²; improved: 18.2 km², deviation: -36.9%), central Coast Mountains (2426.8 km²: 2077.9 km², -14.4%), southern Interior Ranges (2359.4 km²: 2252.6 km², -4.5%). The southern Coast Mountains had the largest number of errors due to debris cover but overall, this error was small (<0.1%). Our revised extents from 1985 for British Columbia contain about 1.5% less ice than the original mapped TRIM glacier extents.

4.2. Regional glacier characteristics and glacier recession

Glaciers with an area between 0.1 and 1.0 km² represent the most frequent size class in all regions except the St. Elias Moun-

tains, where a few large glaciers (>100 km²) cover a large area (Fig. 5). In most other regions, the size class between 1.0 and 5.0 km² covers the largest fraction of terrain. In 1985, mean glacier size varied between 0.3 km² on Vancouver Island and 7.0 km² in the St. Elias Mountains. Further glacier characteristics are presented by Schiefer et al. (2007, 2008) and are summarized in the introduction (section 1).

We summarize the area changes for the periods 1985–2005, 1985–2000 and 2000–2005 based on our defined mountain regions (Table 2, with examples illustrated in Fig. 6). Glacierized terrain decreased from 30,063.0 km² in 1985 to 26,728.3 ± 962 km² (-11.1 ± 3.8%) until 2005. Approximately 2000 of the original ~14,300 glaciers in the study area disintegrated and as a result, the estimated number of glaciers increased by ~3000 between 1985 and 2005. Approximately 300 glaciers disappeared during the same period of time.

Analysis of the corresponding change in glacier area consistently indicates a greater percentage loss for small glaciers across the study area than for large ones (Fig. 7), although the absolute loss is much lower than for the larger glaciers. The largest total loss is for glaciers in the 1–5 km² size class, which also has the largest number of glaciers (~4900). In contrast to the relative ice loss, the absolute area loss in

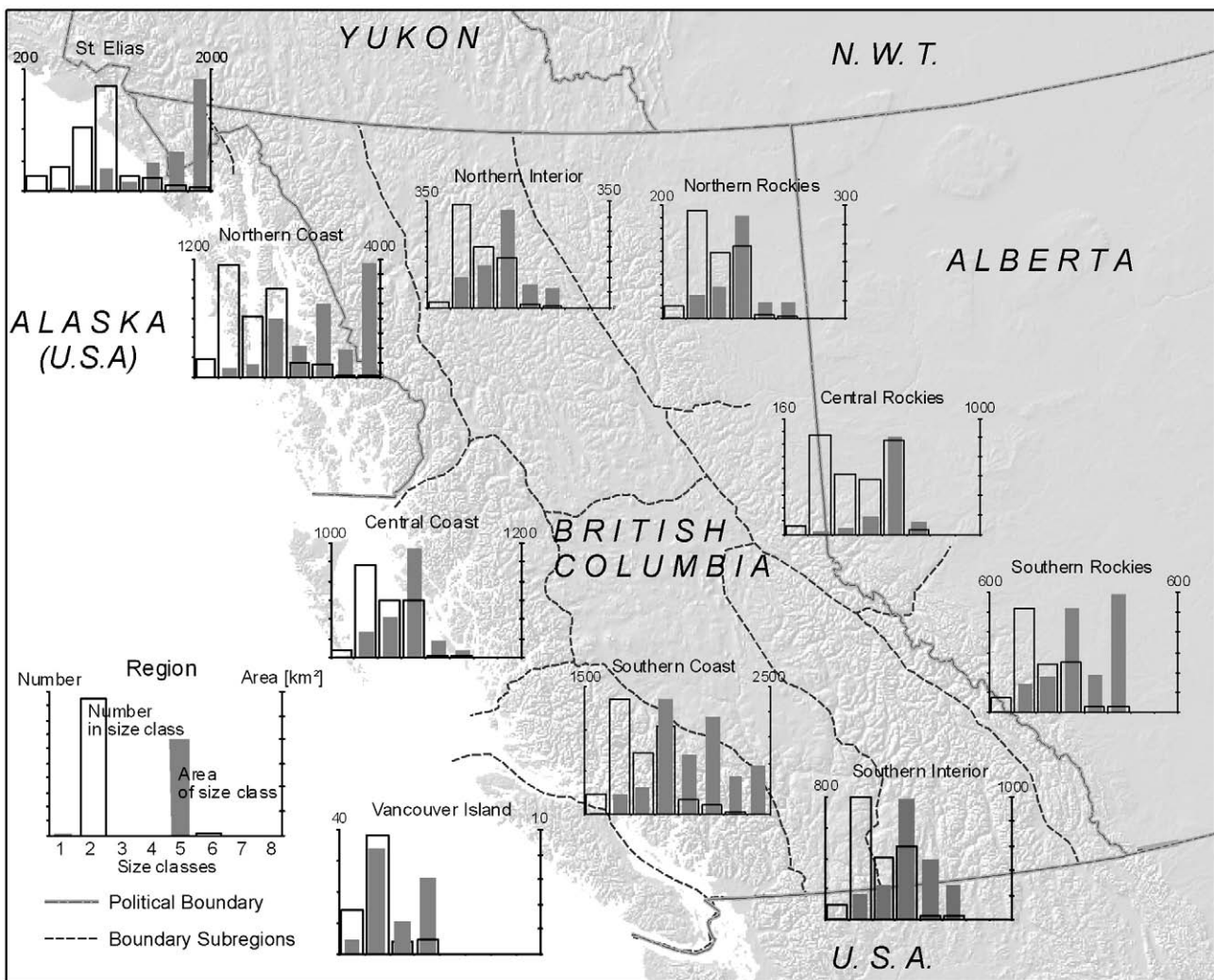


Fig. 5. Diagrams showing the number and covered area for eight different size classes of the glaciers for the ten subregions (year 1985). The size classes are defined as follows: 1: 0.05–0.1 km², 2: 0.1–0.5 km², 3: 0.5–1.0 km², 4: 1.0–5.0 km², 5: 5.0–10 km², 6: 10–50 km², 7: 50–100 km², 8: >100 km².

Table 2
Glacier area and area changes, 1985–2005 for the inventory of Western Canada.

Region	Area 1985 [km ²]	Area 2000 [km ²]	Area 2005 [km ²]	Number of Glaciers (85)	Number of Glaciers (05)	Mean size (85) [km ²]	Area change 85–05 [km ²]	Annual change 85–05 [km ² a ⁻¹]	Area change 85–05 [%]	Area change 85–00 [%]	Area change 00–05 [%]	Annual rate 85–05 [% a ⁻¹]	Annual rate 85–00 [% a ⁻¹]	Annual rate 00–05 [% a ⁻¹]
SE	36156 (87)	No data	33304 (04)	510	647	7.01	-2852 ± 122.6	-15.9 ± 6.8	-7.9 ± 3.4	No data	No data	-0.44 ± 0.19	No data	No data
NC	108632 (83)	3983.0 (99)	100291.1 (05)	3131	3746	3.47	-834.1 ± 367.0	-37.9 ± 16.7	-7.7 ± 3.4	-4.4 ± 4.1	-3.1 ± 4.1	-0.35 ± 0.15	-0.27 ± 0.25	-0.44 ± 0.58
2000 cv.	41642 (83)		38550 (05)				-3092 ± 133.0		-7.4 ± 3.4			-0.34 ± 0.15		
CC	20779 (87)	No data	16250 (05)	2293	2962	0.91	-452.9 ± 101.9	-25.2 ± 4.8	-21.8 ± 4.9	No data	No data	-1.21 ± 0.27	No data	No data
SC	7911.7 (87)	7409.4 (00)	7097.3 (04)	3620	4507	2.10	-814.4 ± 300.5	-47.9 ± 14.4	-10.3 ± 3.8	-6.3 ± 4.5	-3.9 ± 4.5	-0.61 ± 0.22	-0.49 ± 0.34	-0.79 ± 0.86
VI	182 (87)	No data	14.5 (05)	61	65	0.30	-3.4 ± 1.24	-0.20 ± 0.04	-20.0 ± 7.3	No data	No data	-1.11 ± 0.40	No data	No data
NI	6969 (85)	No data	529.9 (05)	729	1083	0.96	-167.0 ± 31.7	-8.65 ± 1.12	-24.0 ± 4.6	No data	No data	-1.20 ± 0.23	No data	No data
SI	22526 (85)	2034.1 (01)	19104 (06)	1855	2304	1.21	-342.2 ± 98.9	-16.3 ± 3.1	-15.2 ± 4.4	-10.5 ± 5.1	-5.5 ± 5.3	-0.72 ± 0.21	-0.66 ± 0.32	-0.92 ± 0.89
NR	4968 (86)	448.6 (01)	418.0 (06)	464	540	1.07	-78.8 ± 22.8	-3.94 ± 0.74	-15.9 ± 4.6	-9.7 ± 4.9	-6.2 ± 5.2	-0.79 ± 0.23	-0.69 ± 0.35	-1.03 ± 0.86
CR	509.1 (86)	No data	420.0 (06)	361	462	1.41	-89.1 ± 20.9	-4.46 ± 0.82	-17.5 ± 4.1	No data	No data	-0.88 ± 0.21	No data	No data
SR	1587.0 (84)	1447.7 (00)	1351.7 (06)	1089	1271	1.46	-235.3 ± 65.2	-10.70 ± 2.3	-14.8 ± 4.1	-7.5 ± 5.2	-7.2 ± 5.7	-0.67 ± 0.19	-0.47 ± 0.36	-1.21 ± 0.96
Whole inventory	30,063.0		26,728.3	14,329	17,595	2.10	-335.8 ± 1141.9	-166.74 ± 48.1	-11.1 ± 3.8	No data	No data	-0.55 ± 0.19	No data	No data
2000 cv.	16,389.8	15,322.8	14,615.2	n.c.	n.c.	2.10	-1774.6	88.73	-10.8 ± 3.5	-6.5 ± 4.5	-4.3 ± 4.6	-0.54 ± 0.17	-0.43 ± 0.30	-0.86 ± 0.88
BC only	28,232.8		25,218.2	13,403	16,428	2.11	-3056.0 ± 990.4	-152.8 ± 41.0	-10.8 ± 3.5	No data	No data	-0.54 ± 0.17	No data	No data
Alberta	1053.5		785.7	926	1167	1.14	-267.9 ± 43.2	-13.39 ± 1.8	-25.4 ± 4.1	No data	No data	-1.27 ± 0.20	No data	No data

Region codes: SE: St. Elias, NC: northern Coast, CC: central Coast, SC: southern Coast, VI: Vancouver Island, NI: northern Interior, SI: southern Interior, NR: northern Rockies, CR: central Rockies, SR: southern Rockies. The dates in brackets (abbreviated to the last 2 digits) represent the averaged mean of the acquisition dates for the different regions. The row for Whole inventory is set in bold to highlight overall statistics. 2000 cv. refers to the portion mapped for the year 2000.

the northern Coast Mountains ($-834.1 \pm 367.0 \text{ km}^2$) was five times higher than in the northern Interior Ranges ($-167.0 \pm 31.7 \text{ km}^2$), given the former's larger glacierized area. Glaciers on the eastern slope of the southern Rocky Mountains lost $25.4 \pm 4.1\%$ of their area, more than twice as much as the glaciers west of the Continental Divide ($10.8 \pm 3.5\%$). The 2000–2005 shrinkage rate was higher than the 1985–2000 rate but not statistically significant given the large error term and short period of time over which area change was assessed. The highest and lowest loss rates for the period 2000–2005 occurred in the southern Rocky Mountains ($-1.21 \pm 0.96\%$) and northern Coast Mountains ($-0.44 \pm 0.58\%$).

In order to control for differences in glacier area, we compare changes in glacier cover for different size classes (Fig. 8). The highest percent area losses occur in the northern Interior, central Rocky, and central Coast mountains. The lowest losses occur in the St. Elias, the northern and southern Coast mountains, and also for the size class $0.5\text{--}1.0 \text{ km}^2$ on Vancouver Island.

Overall, north and southwest facing glaciers shrank most. However, these glaciers are typically the smallest. Comparing the same size class shows similar area losses for all aspects (Fig. 9). Area loss for the size class $1\text{--}5 \text{ km}^2$, for example, only varies between -13.3 (SE) and -15.4% (N), and so the relative area change by aspect is minor. There is also no significant influence of median glacier elevation on shrinkage rate and absolute ice loss across the study area (Fig. 10).

5. Discussion

5.1. Glacier inventory derived by remote sensing

Our methodology enabled us to compile a multi-temporal glacier inventory using Landsat imagery and other digital data over a large region containing more than 15,000 glaciers within a time frame of less than 1 year. Glacier mapping based on the image-ratio method can be used for glacierized regions that require dozens of Landsat scenes, as effectively as for single Landsat images as utilized by several other studies (e.g. Andreassen et al., 2008; Bolch, 2007; Paul et al., 2003; Paul and Käab, 2005). The time commitment per scene was less than that needed for a single scene as several steps can be done for the whole dataset (e.g. splitting the glaciers, calculating glacier variables). However, additional effort is necessary for merging the polygons obtained from different scenes. We found that existing methods to map debris-covered glaciers and glacial lakes were not feasible given the extensive spatial domain of our study area. We believe that our semi-automated method is faster than manual digitization for regions of extensive ice cover and for multi-temporal glacier inventories where an error of $\pm 3\text{--}4\%$ is acceptable. Time efficiency and small errors are important prerequisites for glacier monitoring in the Global Terrestrial Network for Glaciers (GTN-G) as part of the global climate related monitoring programs (GTOS/GCOS). An additional advantage of the selected image-ratio method is its reproducibility (Paul and Andreassen, 2009).

The availability of ice polygons for British Columbia from earlier mapping facilitated the generation of the new inventory and helped eliminate misclassified pixels. However, these polygons were generated within a general mapping program on the basis of permanent snow and ice and needed editing due to partly incorrect glacier delineation, indicating that such outlines should be used with caution.

The presented method to separate glacier polygons for multiple years based on flow direction can be applied to other regions where a suitable DEM is available. The main limitation of the automated drainage basin delineation is that it relies on the quality of the DEM, which is typically prone to errors in steep terrain or with low-contrast imagery. The SRTM DEM or the global ASTER DEM (Hayakawa et al.,

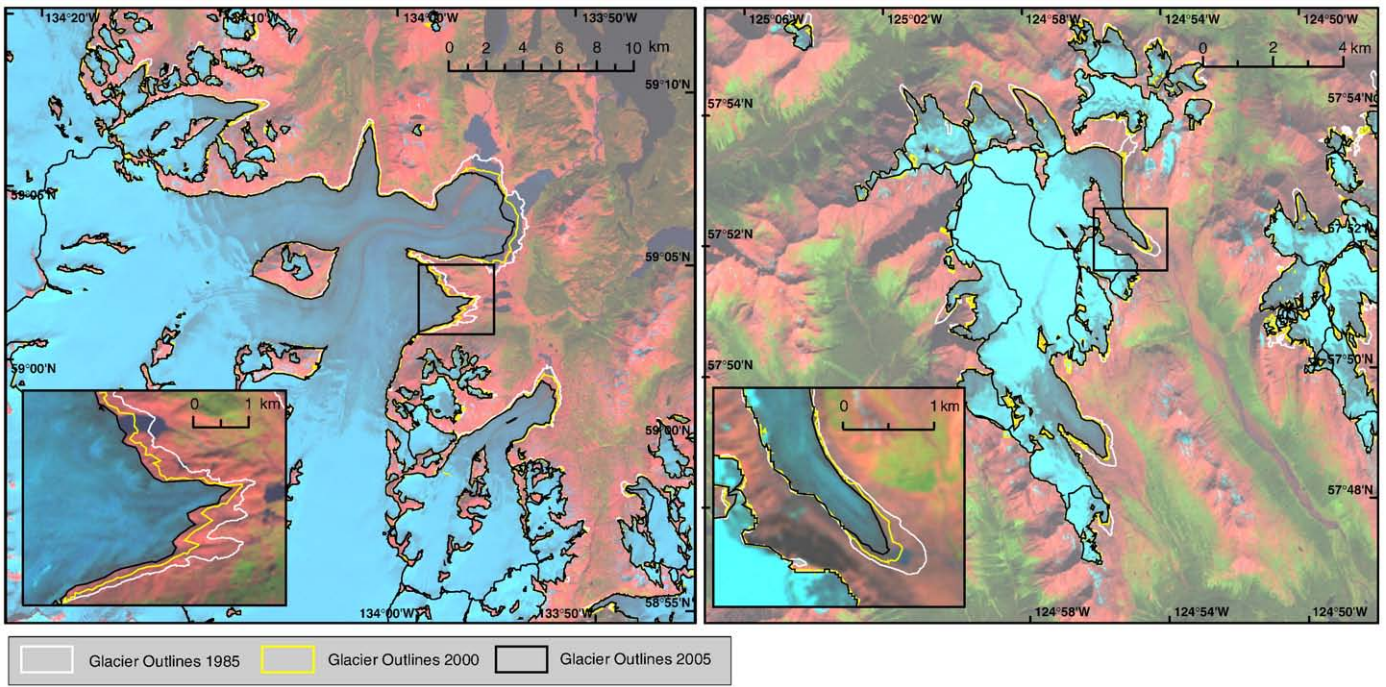


Fig. 6. Examples of glacier recession 1985–2005; left: Llewellyn Glacier in the northern Coast Mountains, right: Lloyd George Icefield in the northern Rocky Mountains.

2008) may enable our approach in remote mountainous terrains that otherwise lack a suitable DEM. The DEM for our study area was accurate for mountain ridges, slopes and glacier tongues, but accumulation areas of larger ice fields contained artefacts affecting the position of their ice divides.

5.2. Glacier area loss

The observed glacier shrinkage in western Canada is in line with the findings of many other glaciated mountain ranges throughout the world (Barry, 2006; WGMS/UNEP, 2008).

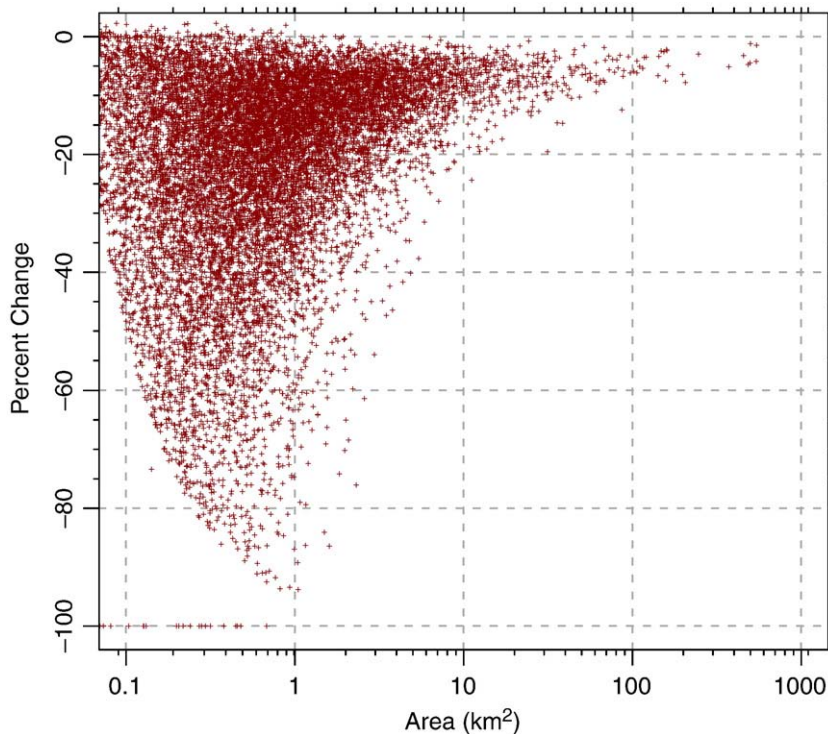


Fig. 7. Relative change in glacier area 1985–2005 versus initial glacier area.

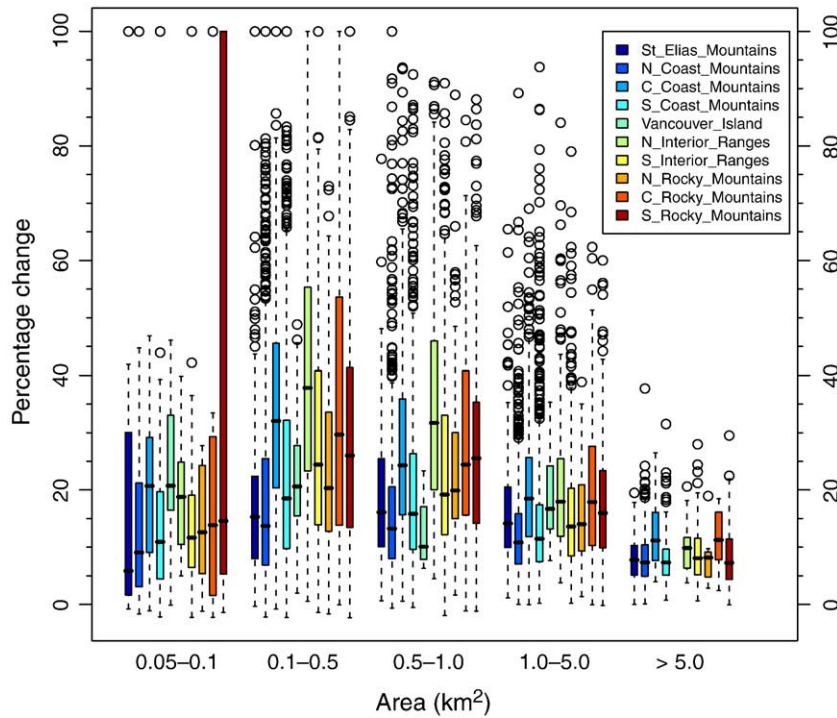


Fig. 8. Glacier area loss 1985–2005 for different size classes (size in 1985) in the different regions. Middle of box is median and box width defined by interquartile range (25 and 75 percentiles). Whiskers are 5 and 95 percentiles. Symbols are <5 or >95 percentiles.

Disintegration of glaciers as detected in our study is also observed in the European Alps (Paul et al., 2004b). Apart from area, glacier shrinkage depends on topography, and differences in regional climate. DeBeer and Sharp (2007) found no notable recession of smaller glaciers (<0.5 km²) along their transect in the southern Canadian Cordillera between 1951/1962 and 2001/2002. In a more detailed analysis, DeBeer and Sharp (2009) attribute this

behaviour to local topographic factors: high altitude locations sheltered from solar insolation minimize changes in glacier extent.

Overall, maritime glaciers lost less relative ice cover than glaciers further inland. A higher glacier recession rate in the southern Rocky Mountains in comparison to the Coast Mountains was also observed by DeBeer and Sharp (2007), although with lower respective shrinkage rates of $-0.31\% \text{ a}^{-1}$ (1952–2001, 59 investigated glaciers, mean glacier area 0.68 km² in 1952) and $-0.13\% \text{ a}^{-1}$ (1965–2002, 1053, $\sim 2.3 \text{ km}^2$) compared to our study. However, their study examined glacier fluctuations over a longer period of time including the period in the 1970s/early 1980s when some glaciers in the Canadian Cordillera advanced (Luckman et al. 1987). Glacier advances or slowed recession may also explain the lower shrinkage rates ($-0.58\% \text{ a}^{-1}$) in the upper Bow River for the period 1951–1993 (Luckman and Kavanagh, 2000) or for the lower observed rates ($-1.13\% \text{ a}^{-1}$) in the upper Saskatchewan River (Demuth et al., 2008), both on the eastern slope of the southern Rocky Mountains. The latter value is in the range of our obtained shrinkage rate of $-1.27\% \text{ a}^{-1}$ (1985–2005, ~ 1000 glaciers, $\sim 1.14 \text{ km}^2$) for the Albertan Rocky Mountains. In contrast, VanLoo and Forster (2008) determined an area shrinkage of -1.6% (-51.3 km^2) between 1991 and 2000, an annual rate of $-0.17\% \text{ a}^{-1}$ for the larger icefields in the southern Coast Mountains. This is less than we found for the entire Southern Coast Mountains and underscores the importance of including small glaciers in the analysis. Further investigation is underway to address climatic factors that may help to explain the regional pattern of ice loss that we describe in this study.

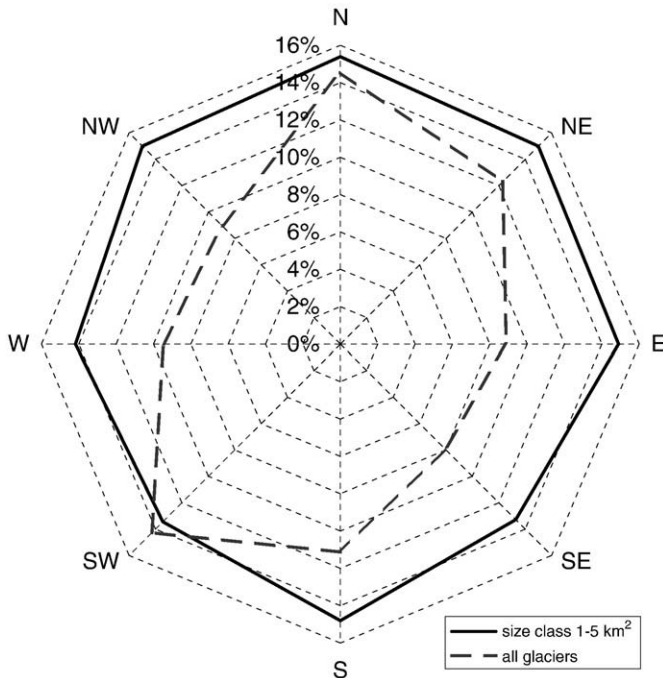


Fig. 9. Diagram showing area loss versus aspect for the whole study area.

6. Conclusions

We provide a comprehensive multi-temporal glacier inventory for British Columbia and Alberta, a region that contains over 15,000

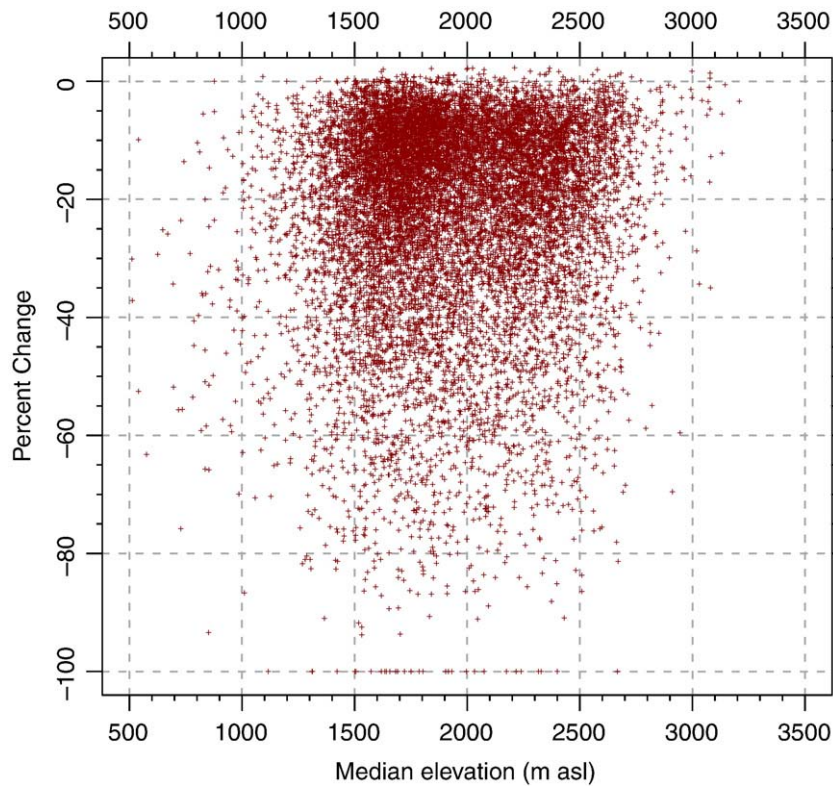


Fig. 10. Relative glacier area loss 1985–2005 versus median glacier elevation.

glaciers, for the years 1985, 2000 (for about half of the area) and 2005, generated in a time frame of less than 1 year. Data used in our study included satellite imagery (resolution 30 m), a DEM (resolution 25 m), and digital outlines of glaciers from 1985. The ratio RED/SWIR (TM3/TM5) worked well to extract glacier ice for the entire study area. Glacier area in western Canada declined $11.1 \pm 3.8\%$ between 1985 and 2005. The highest shrinkage rate in British Columbia was found in the northern Interior Ranges ($-24.0 \pm 4.9\%$), the lowest in the northern Coast Mountains ($-7.7 \pm 4.6\%$). The continental glaciers in the central and southern Rocky Mountains of Alberta, shrank the most ($-25.4 \pm 4.1\%$). However, the shrinkage rate is mostly influenced by glacier size. Regional differences in ice loss are smaller when glaciers of any given size class are examined, and these differences are not explained by aspect. The shrinkage rates have possibly increased across the study area in the period 2000–2005, with the highest increase in the Rocky Mountains.

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Appendix A

Utilized Landsat scenes for the glacier inventory (sources: periods 1985/2000 – Global Landcover Facility, except for 1985 and 1987 scenes purchased from Canadian Centre of Remote Sensing; period 2005 – British Columbia Government, Ministry of Forests and Range).

Nr.	Path/ Row	Inventory 1985 (Acquisition date of Landsat5 TM)	Inventory 2000 (Acquisition date of Landsat7 ETM+)	Inventory 2005 (Acquisition date of Landsat5 TM)
1	042/025	26/07/1985		
2	043/024		23/09/2001	28/08/2006
3	043/025	04/09/1991	23/09/2001	28/08/2006
4	044/024	02/08/1988	14/09/2001	19/08/2006
5	044/025	02/08/1988	14/09/2001	19/08/2006
6	045/023	31/07/1985	17/08/2000	26/08/2006
7	045/024	15/09/1990	17/08/2000	26/08/2006
8	046/023	22/09/1990	25/09/2000	17/08/2006
9	046/024	22/09/1990	25/09/2000	17/08/2006
10	046/026	22/09/1990		28/09/2004
11	047/022	09/10/1988	21/08/2002	23/07/2006
12	047/023	09/10/1988	21/08/2002	18/08/2004
13	047/025	13/09/1990	14/09/1999	02/08/2004
14	047/026	15/08/1991		06/08/2005
15	048/022	24/08/1992		09/08/2004
16	048/024	03/10/1989	23/09/2000	09/08/2004
17	048/025	20/09/1990	23/09/2000	09/08/2004
18	049/024	15/08/1992		31/07/2004
19	049/025	07/08/1989		16/08/2004
20	049/026	07/08/1989		21/07/2006
21	050/021	22/08/1992		10/08/2005
22	050/024	21/09/1991	21/09/2000	22/07/2004
23	050/025			14/09/2006
24	051/019	16/08/1993	14/08/2001	20/08/2006
25	051/020	03/09/1988	14/08/2001	20/08/2006
26	051/023	26/08/1985		20/08/2006
27	052/019			24/08/2005
28	052/020	25/08/1988		24/08/2005
29	052/021	25/08/1988		24/08/2005

Appendix A (continued)

Nr.	Path/ Row	Inventory 1985 (Acquisition date of Landsat5 TM)	Inventory 2000 (Acquisition date of Landsat7 ETM+)	Inventory 2005 (Acquisition date of Landsat5 TM)
30	052/022	25/08/1988		24/08/2005
31	052/023	08/09/1987		24/08/2005
32	053/019			15/08/2005
33	053/020			27/07/2004
34	053/021			27/07/2004
35	053/022	27/08/1986		27/07/2004
36	054/021	26/08/1989		13/09/2007
37	055/019			13/08/2005
38	055/020	08/09/1986		13/08/2005
39	055/020		01/08/1999	10/08/2004
40	056/020			11/09/2007
41	057/019		03/08/1999	29/07/2006
42	059/018			09/08/2005
43	059/019			09/08/2005
44	061/018			08/08/2005

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