GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L16503, doi:10.1029/2007GL030780, 2007

Recent volume loss of British Columbian glaciers, Canada

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Received 24 May 2007; revised 29 June 2007; accepted 23 July 2007; published 22 August 2007.

[1] We use the Shuttle Radar Topography Mission (SRTM) data and digital terrain models from aerial photography to quantify the change of glacier volume in British Columbia (BC), Canada for the period 1985–1999. We note substantial elevation bias in the SRTM elevations, typically on the order of -12 m km^{-1}. The bias-corrected thinning rate is -0.78 ± 0.19 m a^{-1} which yields an annual volume loss of 22.48 ± 5.53 km^{-3}a^{-1}. This rate of glacier volume loss is 65% of the estimate uncorrected for elevation bias (34.7 km^{-3}a^{-1}) and cautions against the use of uncorrected SRTM data for glacier change studies. Glacier recession in BC could account for ca. 0.67 ± 0.12 mm of sea level rise over the period 1985–1999 (0.05 ± 0.009 mm yr^{-1}) or about 8.3% of the contribution from mountain glaciers and ice caps. The recent rate of glacier loss in the Coast Mountains (17.0 km^{-3}a^{-1}) is approximately double that observed for the previous two decades. **Citation:** Schiefer, E., B. Menounos, and R. Wheate (2007), Recent volume loss of British Columbian glaciers, Canada, *Geophys. Res. Lett.*, *34*, L16503, doi:10.1029/2007GL030780.

1. Introduction

[2] Glacier monitoring programs indicate that most mountain glaciers lost mass during the last three decades [*Kaser et al.*, 2006]. The consequences of diminishing glacier cover include rising sea level [*Arendt et al.*, 2002], reductions in freshwater availability [*Barnett and Lettenmaier*, 2005], and increased vulnerability of aquatic ecosystems to low-flow conditions during summer [*Stahl and Moore*, 2006]. Land managers and policy makers require accurate glacier inventories to better prepare for changes in glacier cover brought about by climate change. Studies reveal substantial glacier contraction in the northwest region of BC [*Arendt et al.*, 2002; *Larsen et al.*, 2007]. We report on the recent loss of glacier volume for all of British Columbia (BC), Canada. BC contained 28,826 km^2 of glacierized terrain in the 1980s, and this extent represents 4% and 23% of the global and conterminous North American glacier cover respectively [*Williams and Ferrigno*, 2002].

2. Data and Methodology

[3] We used digital elevation models (DEMs) from spaceborne radar and aerial photography to calculate changes in glacier volume over the period 1985–1999. In February 2000, the Shuttle Radar Topography Mission collected interferometric synthetic aperture radar data processed to produce a DEM (http://seamless.usgs.gov) covering 60°N to 57°S latitude with a 3 arc second resolution and a geocoding accuracy of ±12.6 m [*Farr et al.*, 2007]. The projected SRTM resolution for BC is 95 m and only 3% of the glacierized terrain did not have SRTM coverage. We obtained a 25 m DEM based on aerial photography from the Ministry of Sustainable Resource Management, Government of BC. The photographs were collected in 1982–1988 during late summer, and the median date weighted for mapped area is 1985. This photography was also used to map glacier extents at 1:20,000 as a product of the Terrain Resource Information Management (TRIM) program. The reported horizontal and vertical accuracy of TRIM data is ±10 and ±5 m respectively [*British Columbia Ministry of Environment, Lands and Parks*, 1992].

[4] We also analyzed older 1:50,000 map data for the Andrei and Lillooet icefield regions in the Coast Mountains which we obtained from the Canadian National Topographic Database (NTDB) to quantify any latitude-dependence in the rate of glacier recession (Figure 1). The NTDB data include glacier and vegetation extents, and 30 m contours. Horizontal accuracy of NTDB contours is ±125 m for uninhabited regions whereas vertical error is ±25 m [*Geomatics Canada*, 1996].

[5] To estimate changes in surface elevation through time, we differenced our geographically aligned DEMs and calculated changes in glacier volume by summing elevation differences within the glacier polygons and multiplying by the glacier extents in the earlier of the two DEMs. We assessed the magnitude and spatial distribution of vertical errors by analyzing terrain where elevation differences between DEMs should be negligible (Figure 2). We use the term 'barren terrain' to define unvegetated areas (obtained from the NTDB planimetric data) that are at least two pixels (190 m) from glacier margins. This buffer is required to exclude regions where elevations may have changed due to surface lowering of debris-covered ice or where subaerial erosion of moraines occurred. We completed the error analysis for the differenced SRTM and TRIM data using the NTDB mapsheets as a grid to assess the spatial pattern of vertical errors throughout the study area (Figure 1).

3. Elevation Change Over Ice-Covered and Ice-Free Areas

3.1. Ice-Free Terrain Biases

[6] Unlike the 'bare-earth' elevation models of TRIM and NTDB, the SRTM DEM is based on 'first-return' radar signal processing and is affected by forest canopy height [*Farr et al.*, 2007], which exceeds 20 m for much of BC. The observed 'thickening' over vegetated terrain is undoubtedly due to this effect (Figure 2). Our analysis of

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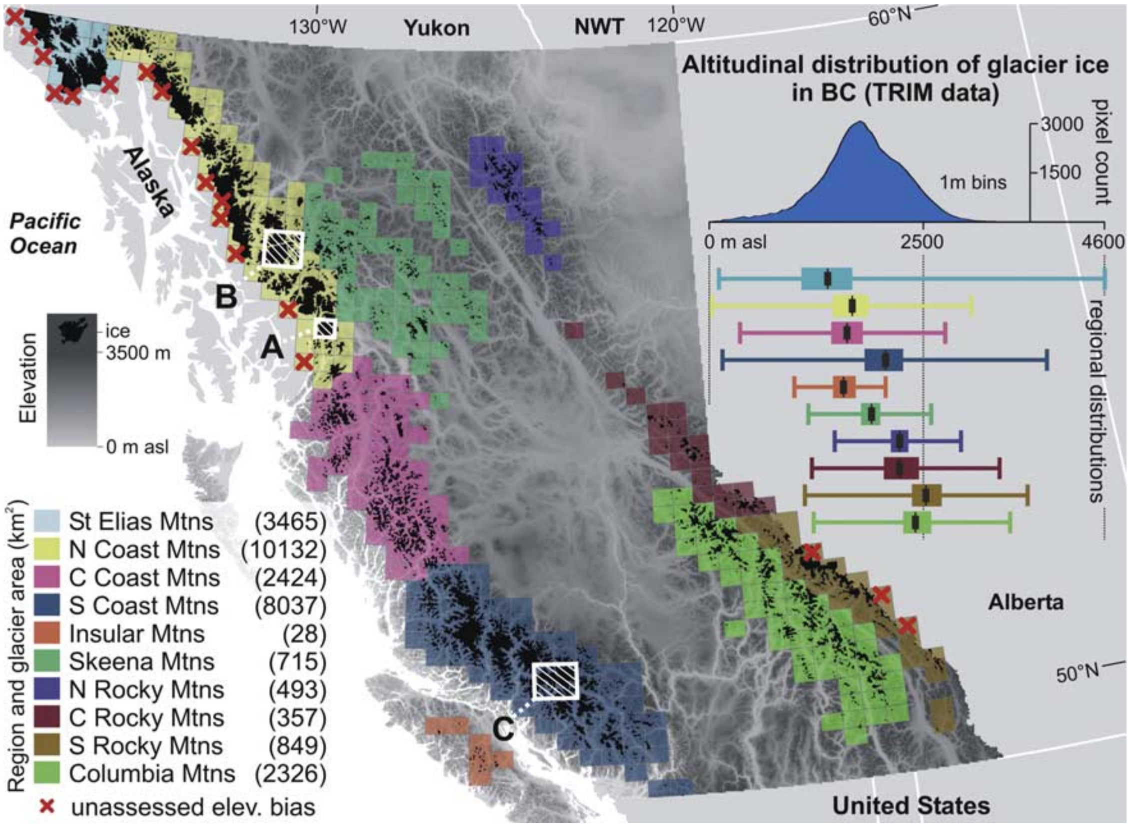

Figure 1. Hypsometric shading shows the relief and geographic extent of BC. Regionally color coded areas delimit the 1:50 k NTDB maps which contain glaciers (dark fill). Hatched box A is the area illustrating terrain biases (Figure 2). Hatched boxes B and C are the Andrei and Lillooet icefield areas (regions of SRTM-NTDB analysis). Histogram shows the altitudinal distribution of glacial ice based on TRIM data with underlying box plots indicating the total range (whisker), interquartile range (box), and median (black line) ice elevation by region.

the barren terrain reveals gross differences in height at low elevation and variable elevation biases with altitude throughout the study area. To reduce this bias, we adjusted our elevation difference data for each of the NTDB map grids with a piecewise model which employed a constant height adjustment below a map-specific elevation threshold, typically between 1000–2000 m. A least-squares model was applied to height changes above this elevation (Figure 2). The constant vertical adjustment for low elevation areas ranged from −11 m to +10 m, and most map areas contained an upper elevation bias of −7 to −16 m km^{-1}. We also assessed the elevation-corrected data for slope and aspect bias, but found these errors were less than 1 m. The lack of aspect-related bias confirms the quality of the DEM co-registration as even slight offsets would produce substantial aspect-related bias. A higher standard deviation (σ: ± 20 m) occurs for steep terrain (>40°) compared to ±7 m for gentle topography (<10°). For the 79,420 km^2 of barren terrain (8.8 × 10^6 pixels), σ is ±13.7 m.

[7] Positive autocorrelation (Moran's I; $p < 0.01$) of the parameters from the elevation adjustment models for the grid defined by the NTDB map sheets indicates that the spatial variability of the elevation bias exceeds the scale of the grid which is ≈900 km^2. Systematic, spatial errors may arise from imperfect aerial triangulation control and the use of different geoids between SRTM (Earth Geopotential Model 1996) and TRIM (Canadian Vertical Datum 1928). Maximum height deviation between geoid models is 3 m. Systematic errors at the regional scale for TRIM should be relatively small due to the accuracy of geodetic control and modern analytical photogrammetry. All of these low-frequency biases present in the height anomaly surfaces were effectively removed by the piecewise adjustment functions.

[8] At scales finer than the NTDB grid (Figure 1), we observed some systematic height deviations over barren terrain which were associated with thinning of debris covered ice and subaerial erosion. The use of a buffer wider than 190 m around the glaciers would limit a reliable altitude distribution of pixels of barren terrain and would have constrained our ability to correct the observed elevation bias. We use σ of the barren terrain height differences (SRTM-TRIM) to quantify the random error in our differenced map data. The moderately high standard deviation observed (13.7 m), however, does not account for the error reduction which would occur by averaging elevation changes over large regions. To produce a standard error (SE_z) for height differences in the barren terrain, we reduced our sample size to account for spatial autocorrelation [*Bretherton et al.*, 1999] at the DEM grid scale. After weighting each SE_z by the area it represents, we obtained an average estimate of ±2.1 m for SE_z. We were unable to determine how representative this error is for ice covered terrain because of the lack of in situ elevation measurements

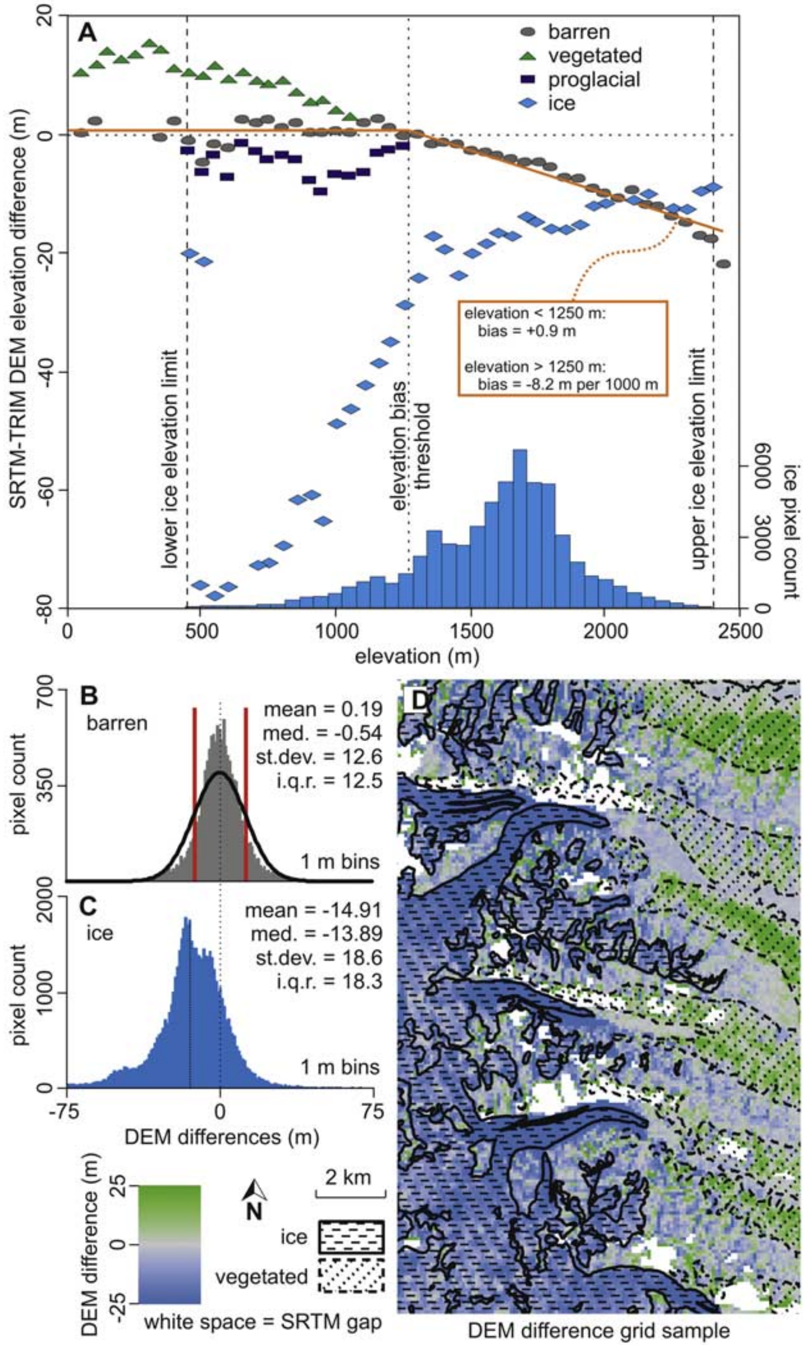

Figure 2. (a) SRTM-TRIM elevation differences for NTDB sheet 103P13 (A in Figure 1) over barren, vegetated, proglacial, and glacierized terrain. Histogram shows the altitudinal distribution of ice cover. Piecewise linear adjustment for bias correction shown by red line. (b) Histogram and statistics of elevation deviations for barren terrain with interquartile range (vertical red lines) and Gaussian fit (black line). (c) Histogram and statistics of elevation differences for ice covered terrain. (d) Surface elevation change over moderately glacierized terrain.

over glaciers. Systematic errors may also arise in the SRTM data due to radar penetration of snow cover over the glaciers; however, it has been determined that in the Alps the SRTM data record a surface in the ablation zone that is representative of the preceding ablation season [*Rignot et al.*, 2001; *Berthier et al.*, 2006]. Greater uncertainty is expected in accumulation zones due to heterogeneous radar penetration in SRTM data and the poor contrast in the TRIM photography due to snowcover.

[9] The TRIM-NTDB height-anomaly surface revealed complex elevation biases throughout the barren terrain. These biases may arise from differences in the quality of geodetic control for these optically-derived DEMs and from interpolation errors that arise from using the NTDB contours. The Andrei and Lillooet icefields each comprise four NTDB map sheets, and elevation biases were linear for the altitudinal range of ice cover. For these icefields, we observed vertical offsets up to 20 m and elevation adjust-

Table 1. Changes in Glacier Volume per Mountain Region

Mountain Region	Ice Area, km^2	Volume Change, km^3 a^{-1}	Thinning Rate,[a] m a^{-1}
St. Elias	3465	−2.69 ± 0.60[b]	−0.78 ± 0.17[c]
N. Coast	10132	−8.41 ± 1.92	−0.83 ± 0.19
C. Coast	2424	−1.47 ± 0.39	−0.61 ± 0.16
S. Coast	8037	−7.13 ± 1.82	−0.89 ± 0.23
Insular	28	+0.004 ± 0.002	+0.13 ± 0.06
Skeena	715	−0.42 ± 0.11	−0.58 ± 0.16
N. Rocky	493	−0.28 ± 0.07	−0.57 ± 0.15
C. Rocky	357	−0.31 ± 0.09	−0.86 ± 0.24
S. Rocky	849	−0.54 ± 0.13	−0.64 ± 0.15
Columbia	2326	−1.23 ± 0.31	−0.53 ± 0.13
All regions[d]	28826	−22.48 ± 5.53	−0.78 ± 0.19

[a]Rates are spatially weighted to account for variable acquisition date of the TRIM data.
[b]Product of thinning rate error and ice area.
[c]Area and elevation weighted to account for systematic and random errors.
[d]Area weighted averages and error terms.

ments of 7 and −14 m km^{-1}, respectively. Slope and aspect associated biases were negligible, but σ exceeds ±20 m for the barren terrain. A similar approach to the TRIM analysis yields a value of SE_z of 1.8 m.

3.2. Calculated Volume and Mass Changes

[10] The regional error terms are area and elevation weighted to account for random errors (SE_z) in the ablation area and both random and uncorrected systematic error (E_{sys}) in the accumulation zones. Accumulation errors are caused by poor photographic contrast which we estimate as the reported vertical errors for the TRIM and NTDB data. Total error in annual thinning rates for the accumulation zone is the root sum of SE_z^2 and SE_{sys}^2. We assume an accumulation area ratio of 0.6 for the glacierized regions, and we also use this ratio to derive an area and elevation weighted density for mass lost from glacierized terrain

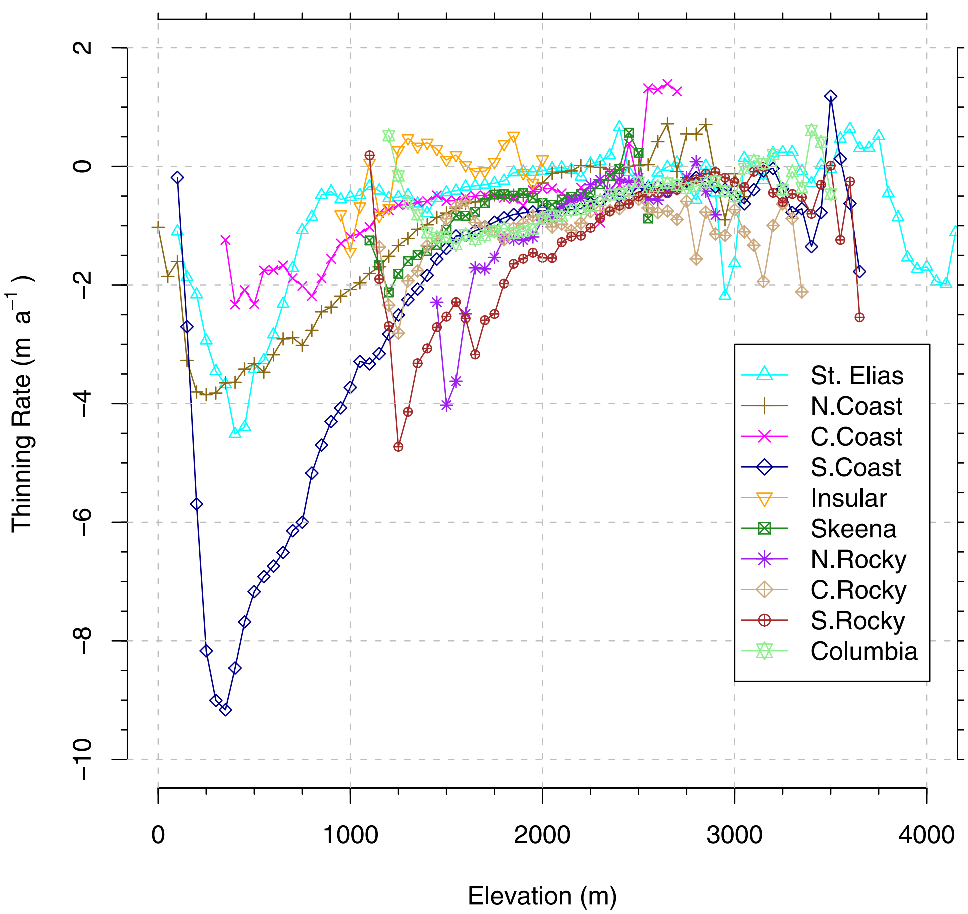

Figure 3. Observed glacier thinning rates vs. altitude for the SRTM-TRIM data for the different regions defined in Figure 1.

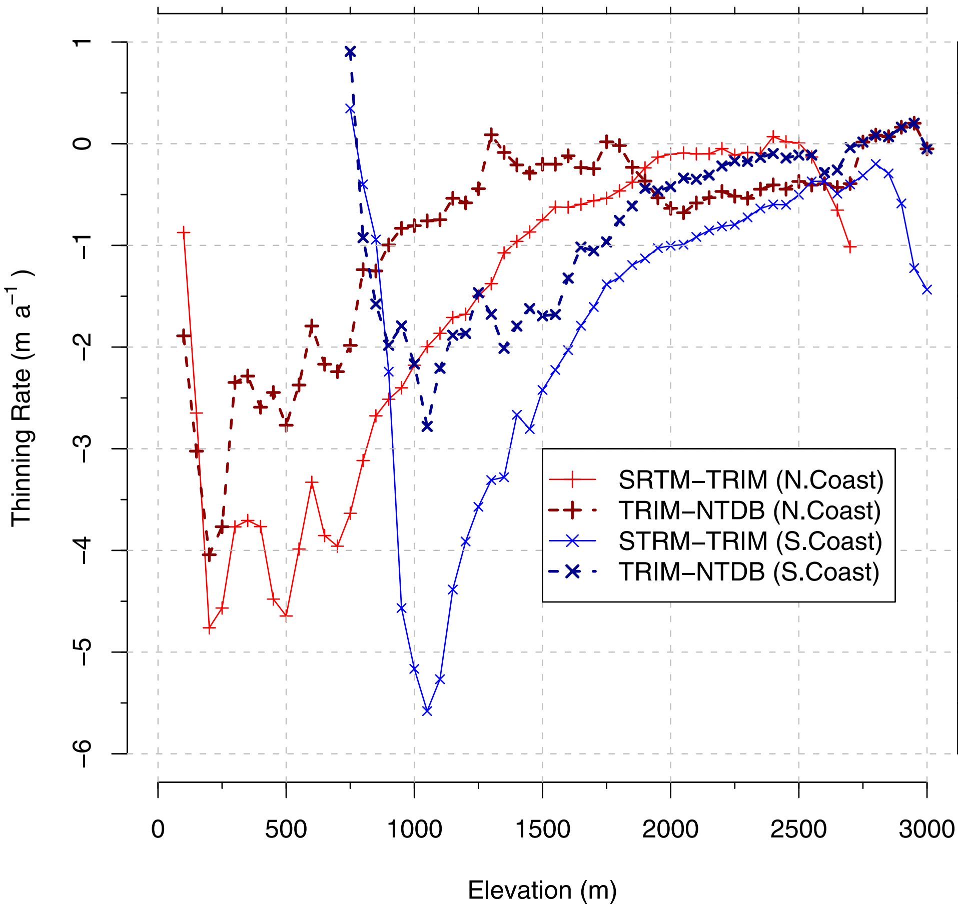

Figure 4. Thinning rates vs. elevation for the SRTM-TRIM and TRIM-NTDB data for the Andrei and Lillooet icefields (B and C in Figure 1).

(900 and 550 kg m^{-3} for the ablation and accumulation areas respectively). A conservative density estimate for the accumulation zone is used to account for a rise in equilibrium line altitudes over the period of study.

[11] The province-wide rate of glacier thinning is -0.78 ± 0.19 m a^{-1}, which when multiplied by the 28,826 km^2 area of TRIM ice cover, yields a volumetric change rate of 22.48 ± 5.53 km^3 a^{-1} (Table 1). Regional glacier thinning rates vary from -0.53 ± 0.13 to -0.89 ± 0.23 m a^{-1}, and the coastal ranges lost the largest fraction of ice (Table 1). As expected, glaciers thinned most at low elevations and these rates decline with altitude (Figure 3).

[12] The observed thickening of Insular Mountain glaciers is likely spurious and caused by the small glacierized area which is situated at high elevation for this region (Table 1). Indeed, we note many irregular and striped regions in our height-change maps at high elevations where glaciers apparently thickened. Some of this variability is revealed at highest elevations in the altitudinal distribution of regional glacier thinning rates (Figure 3). High-elevation cirque glaciers and snowfields would be most prone to low contrast errors and SRTM penetration. The bias-corrected thinning rates for Place (-0.79 m a^{-1}) and Helm (-0.77 m a^{-1}) glaciers when converted to water equivalency are lower than measured thinning rates (-1.15, and -1.3 m a^{-1} respectively) based on field monitoring programs [*Haeberli et al.*, 2003]. Inspection of the height anomaly maps, corrected and uncorrected for elevation bias, reveals that the highest regions of these glaciers apparently thickened but no such trend exists in the mass balance records for these glaciers [*Haeberli et al.*, 2003]. We suspect that height changes in these high-elevation zones are erroneous and are caused by interpolation-induced errors caused by poor contrast of the TRIM photography over glacier accumulation areas. Consequently, changes in surface height are most reliable for low elevation regions of large glaciers where photographic contrast is good.

[13] The high variability in the year of NTDB photography limits our discussion of glacier thinning rate in BC prior to the 1980s to the Andrei and Lillooet icefields, which comprise 1477 and 1406 km^2 of glaciated terrain in the northern (57°N) and southern (51°N) Coast Mountains respectively. This TRIM-NTDB comparison provides an earlier estimate of Coast Mountain glacier thinning rates for the two regions which lost the largest fraction of ice during the period 1985–1999 (Table 1). Maximum thinning rates approach -5 m a^{-1} and -6 m a^{-1} for Andrei and Lillooet icefields respectively, and these rates occur within a few hundred meters of the lower elevation limit of ice cover. These rates decline to less than -1 m a^{-1} near the top of the glaciers. Similar to the SRTM-TRIM comparison, the high elevation error from these accumulation zones limits the reliability of surface change rates in these environments. Spatially-averaged rates of glacier surface

lowering obtained for the TRIM-NTDB data were −0.5 ± 0.96 and −0.6 ± 0.93 m a^{-1} for the Andrei (1982–1965) and Lillooet (1988–1970) icefields. These rates are less than half the average thinning rates of −1.1 ± 0.25 and −1.3 ± 0.37 m a^{-1} calculated for the SRTM–TRIM data (Figure 4). The altitudinal pattern of glacier thinning is similar between the two time periods (Figure 3).

4. Discussion and Conclusions

[14] The extensive coverage and high resolution of SRTM data make them a valuable terrain product to assess recent volumetric changes of mountain glaciers [e.g., *Rignot et al.*, 2003; *VanLooy et al.*, 2006; *Larsen et al.*, 2007]. However, it is clear that vertical biases need to be corrected in elevation models before results obtained from differencing DEMs are valid [*Berthier et al.*, 2006]. In our study systematic and random errors arise undoubtedly from both the SRTM and the optically-derived DEMs. In the SRTM data, incompletely compensated oscillations of the antenna mast and the firing of thrusters for attitude control introduce systematic errors of up to ±12.5 m on spatial scales exceeding 50 km [*Farr et al.*, 2007]. These error sources can account for the systematic height biases observed over barren terrain in the SRTM-TRIM comparisons. The elevation bias for high altitude terrain occurs at a comparable scale and may be associated with the acquisition or processing of the SRTM data. We observe isolated surface errors within the optically-derived DEMs (TRIM and NTDB) that greatly exceed reported vertical accuracies in some low contrast regions of glacier accumulation zones.

[15] Similar biases of SRTM elevations are reported for other mountainous terrain, with slopes that range between −7 and −9 m km^{-1} [*Berthier et al.*, 2006]. In BC, this elevation bias exceeds −12 m km^{-1} for over half of the study area. We observe an average elevation bias of −9.8 m km^{-1} for the St. Elias and Northern Coast mountains which is greater than the −2.3 m km^{-1} reported for this region [*Larsen et al.*, 2007]. Without correction for elevation bias, the estimated volumetric change of BC glaciers is 34.7 km^3 a^{-1} or approximately 1.5 times the bias-corrected estimate of 22.5 km^3 a^{-1}. Our bias-corrected thinning rate for the southern Coast Mountains generally accord with observed thinning rates for glaciers in the Pacific Northwest [*Kaser et al.*, 2006].

[16] Our results confirm the accelerated glacier thinning rates reported for the northern Coast Mountains for the latter half of the 20th century [*Arendt et al.*, 2002; *Larsen et al.*, 2007] and generalize these results to the southern Coast Mountains. Taken together, these data reveal the strongly negative mass balance regimes of the late 20th century for glaciers in BC. Our regional estimates of glacier thinning indicate that heavily glacierized mountain systems experienced greatest volume losses. The estimated contribution of this glacier loss to sea level rise is 0.67 ± 0.12 mm over the period 1985–1999 (0.05 ± 0.009 mm a^{-1}) or 8.3% of the global contribution from melting glaciers and ice caps [*Kaser et al.*, 2006]. This estimate uses a conservative value for the density of mass lost from glacierized terrain and does not account for mass lost from debris-covered ice. However, other factors such as an increase in the density of firn, regional differences in the area accumulation ratios, a rise of regional equilibrium line altitudes, or temporally-variable ice dynamics could reduce the estimated ice loss from BC, and by inference, the contribution to sea level rise.

[17] **Acknowledgments.** We thank the BC and Canadian governments for access to TRIM and NTDB data and two anonymous reviewers whose comments substantially improved the quality and clarity of the paper. This work was supported by the Western Canadian Cryospheric Network, funded by the Canadian Foundation for Climate and Atmospheric Sciences.

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