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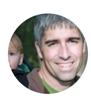

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Glacier change in Garibaldi Provincial Park, southern Coast Mountains, British Columbia, since the Little Ice Age

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ABSTRACT

Fluctuations of glaciers during the 20th century in Garibaldi Provincial Park, in the southern Coast Mountains of British Columbia, were reconstructed from historical documents, aerial photographs, and fieldwork. Over 505 km^2, or 26%, of the park, was covered by glacier ice at the beginning of the 18th century. Ice cover decreased to 297 km^2 by 1987–1988 and to 245 km^2 (49% of the early 18th century value) by 2005. Glacier recession was greatest between the 1920s and 1950s, with typical frontal retreat rates of 30 m/a. Many glaciers advanced between the 1960s and 1970s, but all glaciers retreated over the last 20 years. Times of glacier recession coincide with warm and relatively dry periods, whereas advances occurred during relatively cold periods. Rapid recession between 1925 and 1946, and since 1977, coincided with the positive phase of the Pacific Decadal Oscillation (PDO), whereas glaciers advanced during its negative phase (1890–1924 and 1947–1976). The record of 20th century glacier fluctuations in Garibaldi Park is similar to that in southern Europe, South America, and New Zealand, suggesting a common, global climatic cause. We conclude that global temperature change in the 20th century explains much of the behaviour of glaciers in Garibaldi Park and elsewhere.

1. Introduction

Glaciers are sensitive to changes in climate and are an important element of studies that document past climate change (Global Climate Observing System, 1995; Intergovernmental Panel on Climate Change, 2007). They are being monitored around the world because their current fluctuations have important implications for water supply, fisheries, aquatic ecosystems, and sea-level change. Although data on their activity are now widely available, global databases, including the World Glacier Inventory (Haeberli et al., 1998a; www.geo.unizh.ch/wgms/) and the World Data Center A for Glaciology (Fetterer et al., 2002; nsidc.org/wdc), lack accurate and up-to-date information for about 50% of the world's glaciers (Haeberli et al., 1998b).

Changes in glacier area and length in the 20th century in Europe and several other regions are known in detail from photographs, paintings, and written records (Harper, 1993; Warren and Sugden, 1993; Pfister et al., 1994; Holzhauser and Zumbühl, 2002; Motyka et al., 2002; Rivera and Casassa, 2004). Glaciers in western Canada have not been as extensively studied, although there are notable local exceptions, including parts of the Coast Mountains (Ricker, 1979, 1980; Ricker et al., 1981; Tupper and Ricker, 1982; Ricker et al., 1983; Menounos, 2002; Larocque and Smith, 2003; Evans, 2004; Koch et al., 2004; Kershaw et al., 2005; Osborn et al., 2007), and the Rocky Mountains (Baranowski and Henoch, 1978; Gardner and Jones, 1985; Luckman et al., 1987; Osborn and Luckman, 1988; McCarthy and Smith, 1994; Luckman, 1998, 2000). Available information suggests regional synchroneity in the behaviour of glaciers in western Canada during the 20th century: glaciers retreated from 1900 to 1920, 1930 to 1950, and following 1980; and they advanced between 1920 and 1930 and 1950 and 1970. Yet little is known about changes in glacier area and volume and the rates at which the changes occurred.

The objectives of this paper are to document: (a) frontal variations of glaciers in Garibaldi Provincial Park in the southern Coast Mountains of British Columbia during the 20th century; and (b) changes in total glacier cover over the past 300 years. We relate these changes to regional and global records of climate change.

2. Study area

Garibaldi Provincial Park is located in the southern Coast Mountains, about 70 km north of Vancouver, British Columbia (Fig. 1). Mount Garibaldi, in the southwest corner of the park, reaches 2678 m above sea level (asl) and is less than 20 km from tidewater at the head of Howe Sound. Several other peaks in the park are higher than 2500 masl.

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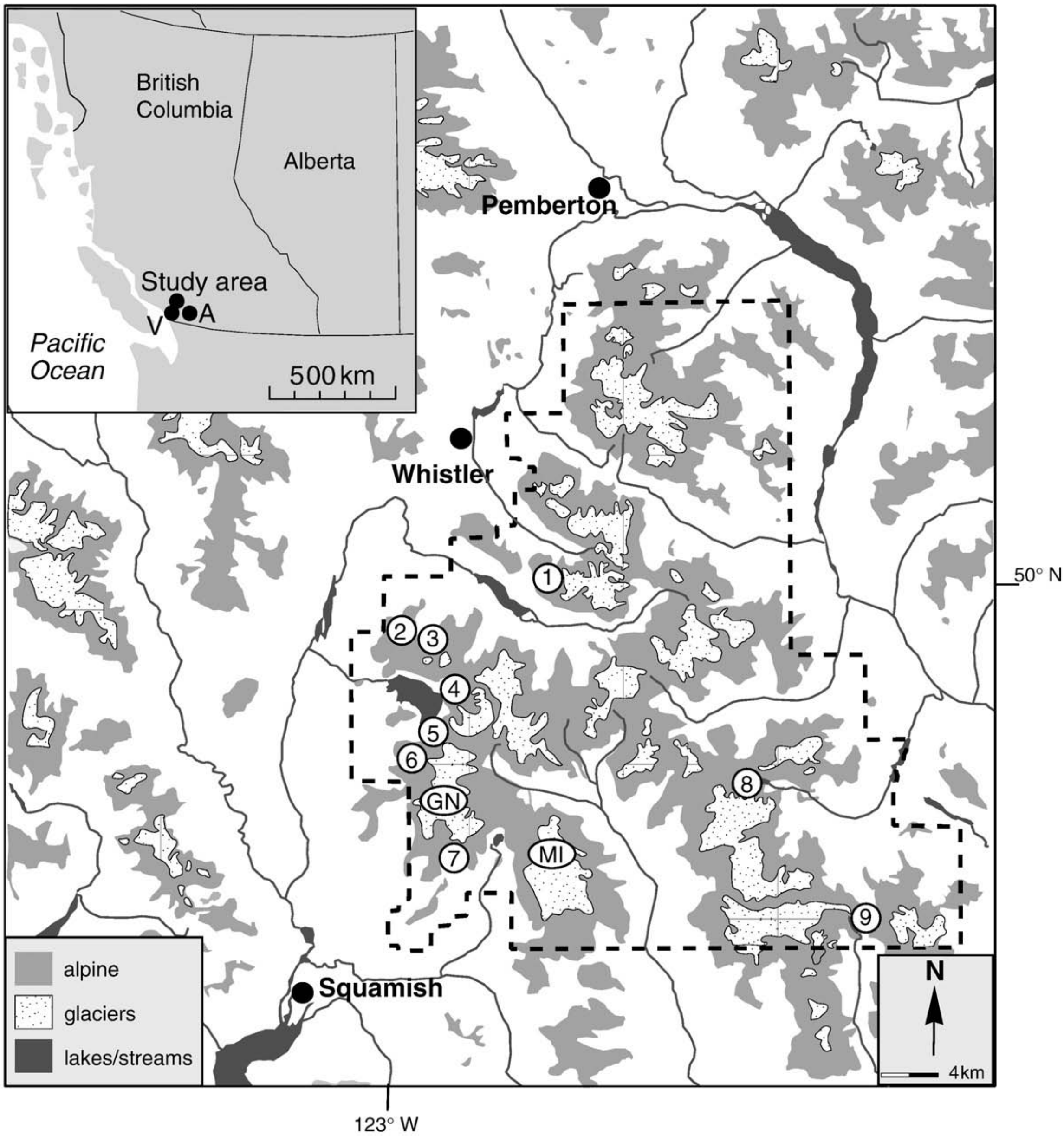

Fig. 1. Location of Garibaldi Provincial Park and its glaciers. 1, Overlord Glacier; 2, Black Tusk Glacier; 3, Helm Glacier; 4, Sphinx Glacier; 5, Sentinel Glacier; 6, Warren Glacier; 7, Garibaldi/Lava glaciers; 8, Snowcap Lakes; 9, Stave Glacier. Also shown are the locations of the Garibaldi Neve (GN), the Mamquam Icefield (MI), Vancouver and Agassiz (V and A on the inset map).

Garibaldi Park has more than 150 glaciers, with a total ice-covered area of 297 km^2 in 1987–1988 when the last comprehensive mapping of glaciers in the park was completed (BC Ministry of Environment, Land and Parks, 2002). The Garibaldi Neve and Mamquam icefields, which each exceed 10 km^2, are the largest bodies of ice in the park.

Table 1
Dates of aerial photographs and satellite imagery (2005) used to reconstruct glacier extents in Garibaldi Park.

Glacier	Year of photographs																	
	1931	1949	1952	1957	1964	1969	1973	1977	1980	1982	1984	1987	1988	1990	1993	1994	1996	2005
Overlord	–	Y	–	–	–	Y	–	–	Y	–	–	Y	–	–	–	–	Y	Y
Black Tusk	–	Y	–	–	–	Y	–	–	–	–	–	–	Y	Y	–	Y	Y	Y
Helm	–	Y	–	–	–	Y	–	Y	–	–	–	–	Y	Y	–	–	Y	Y
Sphinx	–	Y	–	–	Y	Y	–	Y	–	–	–	–	Y	–	Y	–	Y	Y
Sentinel	–	Y	–	–	Y	Y	–	Y	–	–	–	Y	–	–	Y	–	Y	Y
Warren	–	Y	–	Y	Y	Y	Y	Y	–	Y	–	Y	–	–	Y	Y	Y	Y
Garibaldi	–	Y	–	–	–	Y	–	Y	–	Y	–	Y	–	–	Y	Y	Y	Y
Lava	–	Y	–	–	–	Y	–	Y	–	–	Y	Y	–	–	Y	Y	Y	Y
Snowcap	Y	Y	Y	–	–	Y	–	Y	–	–	–	Y	–	–	Y	–	Y	Y
Stave	–	–	Y	–	–	Y	–	Y	–	–	–	Y	–	–	Y	–	–	Y

Notes: 1928–1929 ground photographs were also used for all glaciers except Snowcap and Stave glaciers. Additional photographs were taken from the ground and air between 2002 and 2004.

Table 2
Total and rates of frontal change of glaciers in Garibaldi Provincial Park in the twentieth century.

Period	Behaviour	Change (m)[a]	Rate (m/a)
Overlord Glacier			
ca. 1920	Last moraine formed		
1920s	Retreat	250	28
1929–1949	Retreat	650	33
1949–1969	Retreat/advance	120	6
1969–1980	Advance/retreat	100	9
1980–1996	Retreat	120	8
1996–2002	Retreat	60	10
Helm Glacier			
1910s	Last moraine formed		
1910s–1928	Retreat	<100	ca. 5
1928–1949	Retreat	350	17
1949–1969	Retreat/advance	300	15
1969–1977	Advance	50	6
1977–1990	Retreat	500[b]	38
	Retreat	100[c]	8
1990–1996	Retreat	30	5
1996–2003	Retreat	80	11
Sphinx Glacier			
1900s–1910s	Last moraines formed		
1910s–1928	Retreat	250	17
1928–1949	Retreat	1300	62
	Retreat	400[d]	19
1949–1964	Retreat	600	40
	Retreat	200[d]	13
1964–1969	Retreat/advance	<10	<2
1969–1977	Advance	90[b]	11
	Advance	100[c]	13
	Advance	90[d]	11
1977–1993	Retreat	50	3
1977–1996	Retreat	40	13
	Retreat	50[b]	17
1996–2003	Retreat	50–80	7–12
Sentinel Glacier			
1900s–1910s	Last moraines formed		
1910s–1928	Retreat	200	13
1928–1949	Retreat	800	38
1949–1969	Retreat	80[b]	4
	Retreat	850[c]	43
1969–1977	Retreat	60[b]	7.5
	Retreat	250[c]	31
	Advance	130[e]	16
1977–1993	Retreat	90[b]	8
	Advance/retreat	350[c]	31
	Retreat	220[e]	16
1993–1996	Retreat	10–20	3–7
1996–2003	Retreat	40–50	ca. 7
Warren Glacier			
1900s	Last moraine formed		
1900s–1912	Retreat	Minimal	n/a
1912–1928	Retreat	Minimal[b]	n/a
	Retreat	800[c]	50
1928–1949	Retreat	2000[b]	ca. 95
	Retreat	500[c]	24
1949–1957	Retreat	300	38
1957–1964	Retreat	90	13
1964–1969	Retreat	40–150	8–30
1969–1973	Retreat	80	20
1973–1977	Advance	80	20
1977–1982	Retreat	380	76
1982–1996	Retreat	200	14
1996–2003	Retreat	50	7
Garibaldi Glacier			
1910s	Last moraine formed		
1910s–1928	Retreat	n/a	n/a
1928–1949	Retreat	1100	52
1949–1969	Retreat	300–500	15–25
1969–1977	Retreat	100–200	12–25
Garibaldi Glacier			
1977–1982	Advance	20	4
1982–1996	Retreat	20–40	1–3
1996–2003	Stable	n/a	n/a
Lava Glacier			
1910s	Last moraine formed		
1910s–1928	Retreat	n/a	n/a
1928–1949	Retreat	1000[f]	47
	Retreat	600[b]	28
1949–1969	Retreat	620[f]	31
	Retreat	650[b]	32
1969–1977	Retreat	220[f]	28
	Retreat	20–30[b]	2–4
1977–1984	Retreat	<20[b]	<3
1984–1996	Retreat	160[f]	8.5
	Retreat	40–200[b]	2–11
1996–2003	Retreat	20	3
Snowcap Lakes area			
1900s–1910s[g]	Last moraines formed		
1910s–1931	Retreat	G250	16
	Retreat	S n/a	n/a
	Retreat	T n/a	n/a
1931–1952	Retreat	G900	43
	Retreat	S250	12
	Retreat	T800–900	38–43
1952–1969	Advance	G150	9
	Retreat	S200	12
	Advance	T50	3
1969–1977	Advance	G150	19
	Advance	S150	19
	Advance	T100	13
1977–1996	Advance/retreat	G150	8
	Retreat	S150	8
	Advance/retreat	T130–180	7–10
1996–2004	Retreat	G50	6
	Retreat	S40	5
	Retreat	T30	4
Stave Glacier			
1900s	Last moraine formed		
1900s–1952	Retreat	1300	26
1952–1969	Retreat	620	36
1969–1977	Retreat	200	25
1977–1996	Retreat	750[h]	40
	Retreat	200[d]	11
1996–2002	Retreat	90	15

Note: Rate of change assumes continuous and constant advance or retreat. Dominant behaviour is underlined.
[a] Rates listed for separate tongues where applicable; G: Griffin Glacier; S: Staircase Glacier; T: Thunderclap Glacier.
[b] West.
[c] East.
[d] Southern tributary.
[e] Middle.
[f] South.
[g] Moraines were only dated at Griffin Glacier.
[h] Main.

Moist maritime air masses strongly influence the southwest part of the park, but climate becomes increasingly continental to the north and east. Overall, the climate is humid and cool, with very wet winters and dry summers. Annual precipitation ranges from 1000 mm to more than 3000 mm (water equivalent), with most precipitation falling as snow between October and March.

3. Methods

We utilized a variety of remotely sensed data to determine changes in glacier length, area, and volume over the past 75 years. Frontal

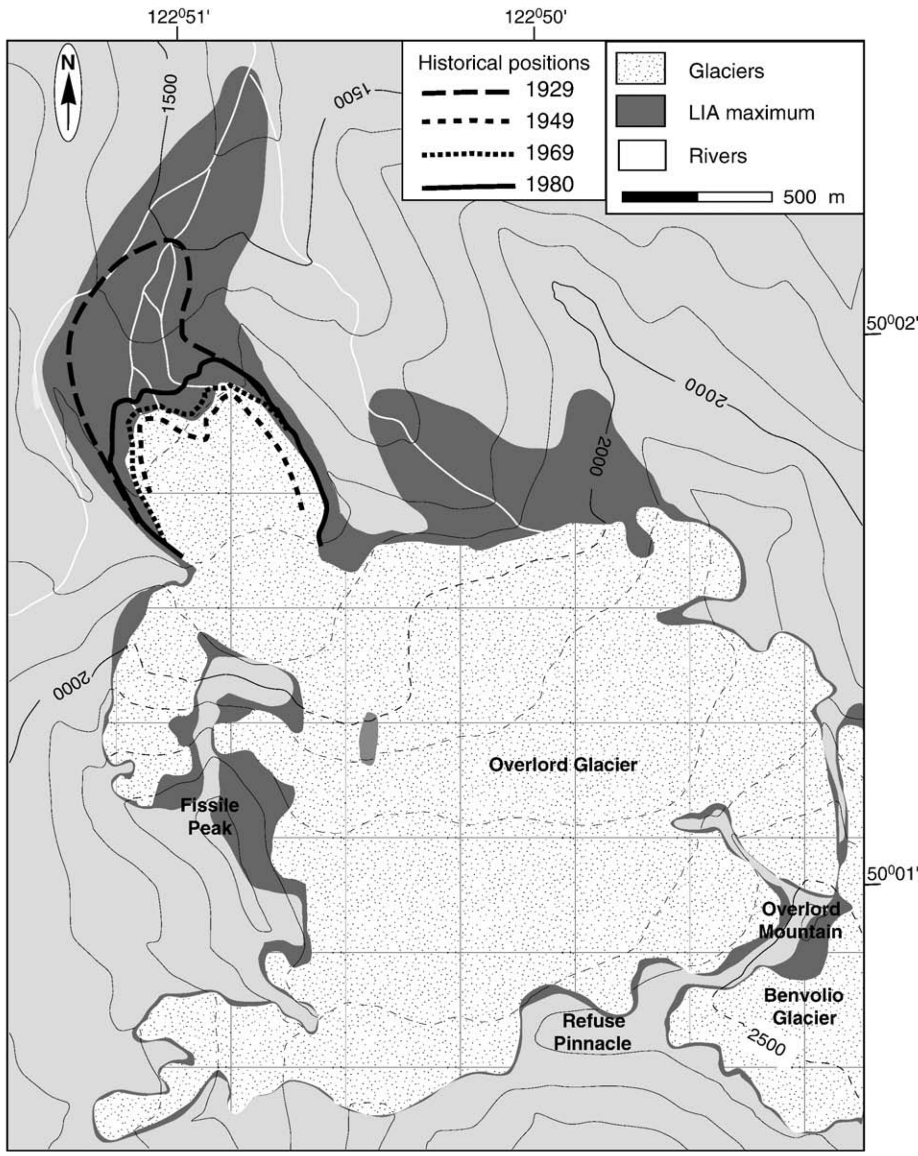

Fig. 2. Map of Overlord Glacier showing its present and maximum Little Ice Age extents and historic margins. Present glacier margin in this and subsequent figures refers to glacier extent in 1996.

changes of thirteen glaciers were reconstructed from oblique photographs and from vertical aerial photographs (Table 1). The oblique photographs were taken in 1928 as part of a geodetic survey of Garibaldi Park. The first topographic map of the park, which showed the extent of glaciers in 1928, was produced from these photographs. We digitized glacier margins and contours from this map to determine changes in glacier volume for outlet glaciers of the Garibaldi Neve since 1928. The map was co-registered to planimetric and digital elevation data acquired through the British Columbia Terrain Resource Inventory Management (TRIM) Program. Horizontal and vertical accuracy of TRIM data based on 1987 and 1988 aerial photographs is ±10 and ±5 m, respectively (BC Ministry of Environment, Lands and Parks, 2002). Root mean squared error (RMSE) of 12 ground control points used to georeference the map is ±9 m, and the contour interval is 30 m. We subsequently produced a 25-m DEM from the 1928 contours for the largest glaciers on the map and determined glacier flowsheds using the same contours.

We estimated elevation change by differencing the co-registered 1928 and 1987 DEMs. Volume losses represent the summation of elevation change within the 1928 glacier polygons. In addition to vertical errors in each DEM, imperfect co-registration could introduce substantial errors in elevation change, especially in areas of steep terrain. We digitized contours of five ridges that were ice-free in 1928 and in Landsat imagery from 2005 (see below) in order to assess errors that could arise from differences in vertical

Table 3
Areal extent of glaciers in Garibaldi Provincial Park at the Little Ice Age maximum, in 1928, 1987–1988, and 2005.

Glacier	Areal extent (km^2/%)				Total recession	Total advance
	LIA max	1928	1987/88	2005	(m)	(m)
Overlord	4.17	3.49/84	3.00/72	2.89/69	1080	200
Black Tusk	5.9	1.12/19	n/a	0.68/12	200–750[a]	n/a
Helm	4.97	4.28/86	1.28/26	0.924/19	960–1360	50
Sphinx	10.64	6.09/57	4.67/44	4.19/39	2315	100
Sentinel	5.7	3.95/69	2.27/40	2.59/45	2140–2520	130
Warren	10.16	9.68/95	5.23/52	4.38/43	2450	80
Garibaldi	7.26	4.32/60	2.96/41	2.61/36	1540–1840[a]	20
Lava	7.79	5.5/71	3.26/42	2.57/33	1400–2020[a]	20
Snowcap	22.6	n/a	11.38/50	9.45/42	n/a	n/a
Thunderclap	n/a	n/a	n/a	n/a	1110	150
Griffin	n/a	n/a	n/a	n/a	1350	300
Staircase	n/a	n/a	n/a	n/a	640	150
Stave	19.91	n/a	11.38/57	9.45/47	2960	n/a

[a] Recession since 1928.

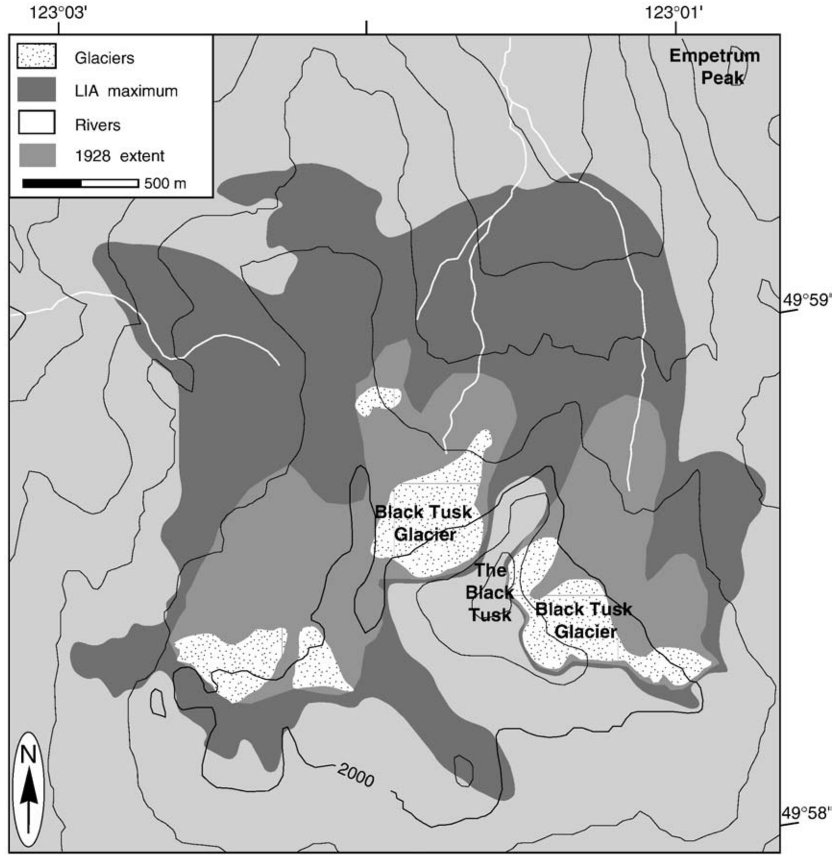

Fig. 3. Map of Black Tusk Glacier showing its present and maximum Little Ice Age extents and historic margins.

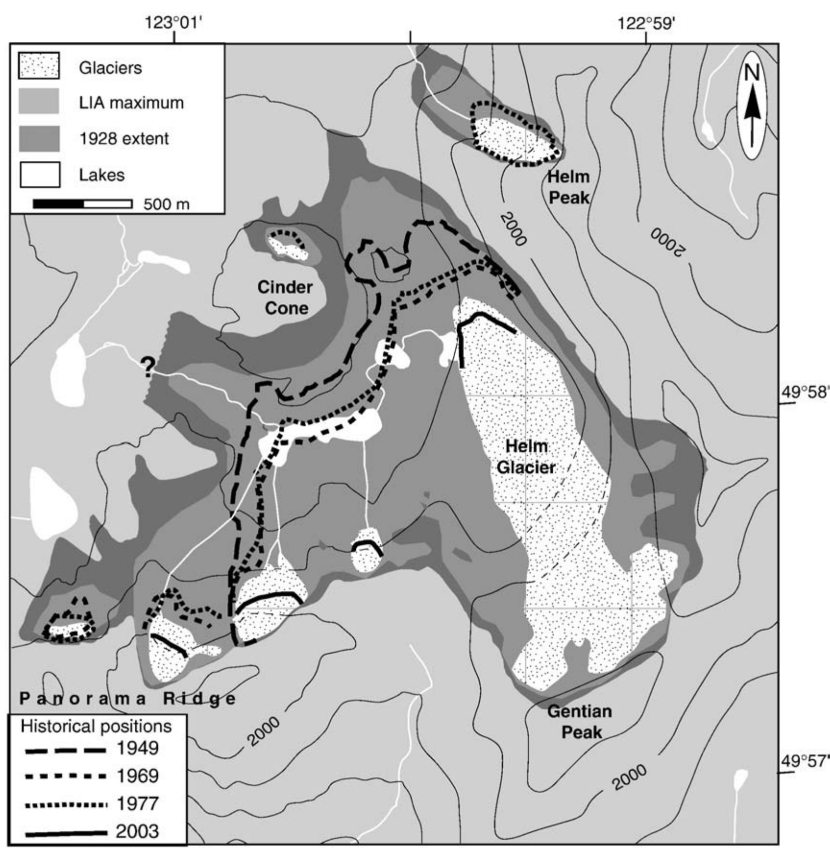

Fig. 4. Map of Helm Glacier showing its present and maximum Little Ice Age extents and historic margins.

data (Schiefer et al., 2007). The area of digitized ice-free terrain was 7.25 km^2. The mean elevation change in the ice-free areas is 0.69 m (standard deviation = 33 m). Using the approach discussed in Schiefer et al. (2007), we obtain an error estimate of ±15.3 m for the elevation change. This estimate incorporates the observed standard error (±3.2 m) of the ice-free area corrected for effective sample size (Bretherton et al., 1999), and a term to account for poor photographic contrast in the accumulation zones of the glaciers (±15 m).

We also mapped glacier extents from a Landsat Thematic Mapper (TM) satellite image acquired on September 6, 2005, to assess changes in glacier extent since 1987–1988. This scene was orthorectified with 20 ground control points obtained from the TRIM digital elevation model with a RMSE of less than ±15 m. We delimited glacier extent by performing a supervised classification of a 5-4-3 band composite of the Landsat scene. This composite exploits the low and high reflectivity of snow in the near infrared (band 5) and visible (bands 4 and 3) portion of the electromagnetic spectrum (König et al., 2001). Debris-covered ice was uncommon and did not pose a problem for our classification algorithm. To compare our results to the TRIM data, we limited our classification of snow and ice to areas that fall within the TRIM glacier polygons. In doing so, we assumed that glaciers did not advance between 1987/1988 and 2005, an assumption subsequently verified using photography and satellite data. The glacier coverage derived from the classification was manually checked and edited for errors.

We examined in greater detail the frontal behaviour of 13 glaciers for which we had decadal aerial photographic coverage. Frontal extents were transferred from aerial photographs onto transparent overlays by comparing distinctive features close to glacier margins that could be identified on sequential photographs, for example large boulders, ponds, and bedrock outcrops. Differences in photo scale, contrast, lighting, surface vegetation, and photographic distortion result in possible errors of up to 20 m in the mapped margins. Former ice-front positions were also determined in the field by using a tape to measure distances between features that could be identified on successive aerial photographs.

We transferred glacier extents from aerial photographs into a GIS to produce a map of Little Ice Age glacier cover. Little Ice Age glacier margins were mapped and dated by tree rings and lichenometry and are reported

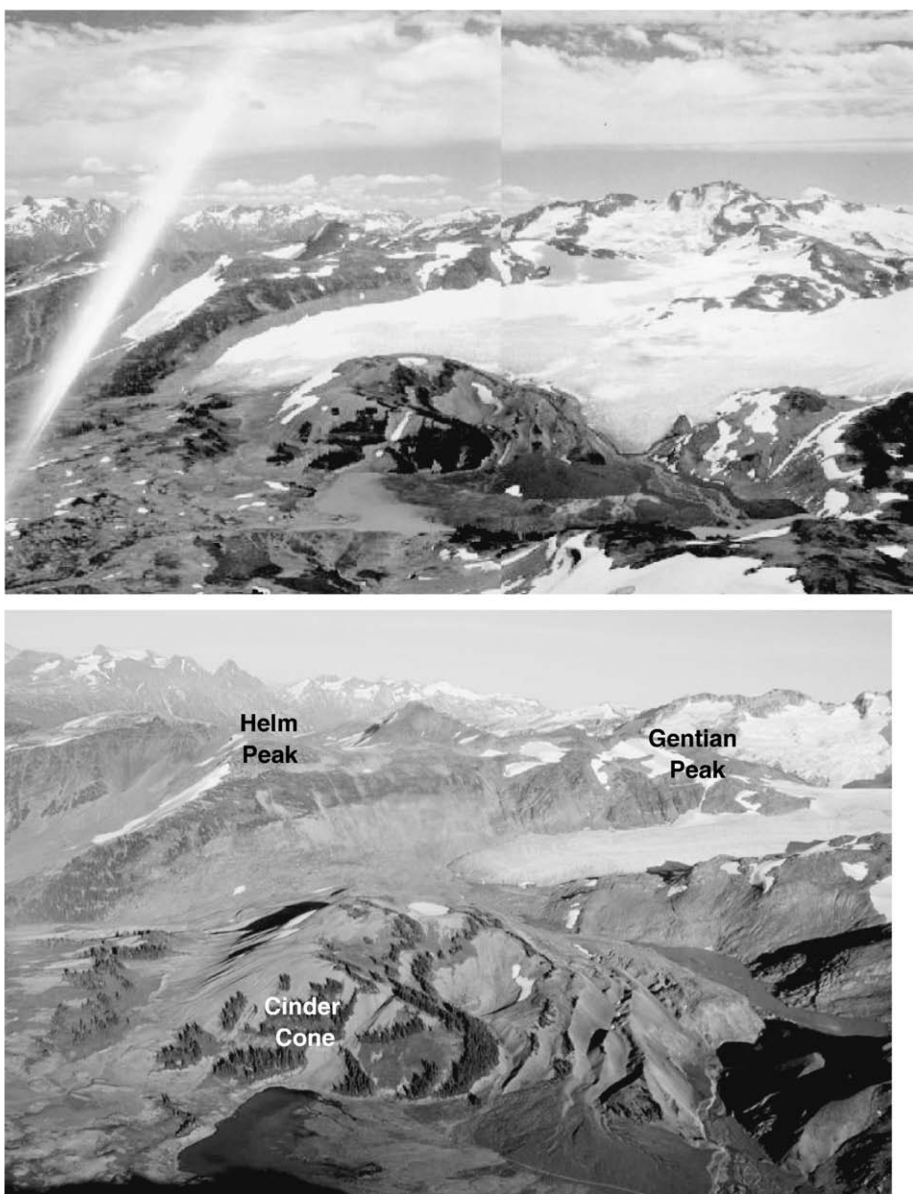

Fig. 5. Photographs of Helm Glacier in 1928 (top; BC Archives I-67145 and 67146) and 2002 (bottom; J. Koch).

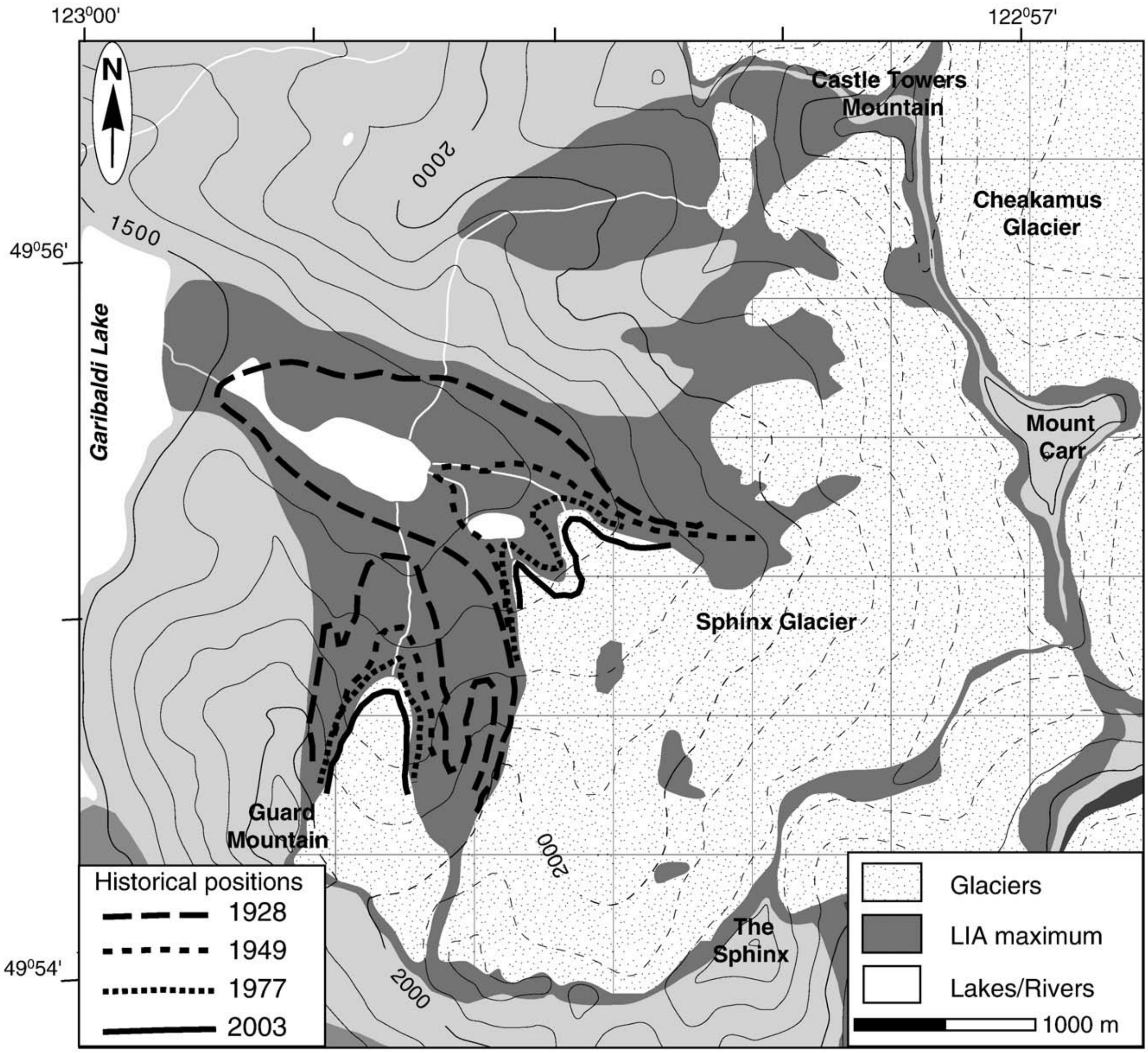

Fig. 6. Map of Sphinx Glacier showing its present and maximum Little Ice Age extents and historic margins.

elsewhere (Koch et al., 2007). A 25-m DEM with artificial illumination highlighted lateral and terminal moraines and glacier trimlines. We also used oblique photographs taken on overview flights of the park between 2002 and 2004, and ground surveys to facilitate the mapping.

4. Results

Comparison of ice extent in Garibaldi Park at the Little Ice Age maximum (AD 1690s–1720s; Koch et al., 2007) and today provides a good estimate of regional ice loss over the past 300 years. Over 505 km^2 of the park was glacierized at the height of the Little Ice Age. This value is a minimum because past ice extent in some cirques could not be determined and because our mapping was restricted to cirques and forefields with glaciers mapped during the TRIM program. Glacier extent in 1987–1988 was 297 km^2, 41% less than in the early 1700s. Based on mapping of individual glaciers, discussed below, over half of this loss occurred after 1920. Between 1987–1988 and 2005, glacier extent decreased an additional 52 km^2, or about 18%. The following sections and Table 2 provide more detailed data for the 13 glaciers that were studied in detail.

4.1. Overlord Glacier

In 2005, Overlord Glacier had an area of 2.89 km^2, about 69% of its maximum Little Ice Age area (Fig. 2; Table 3). The oldest photograph, taken in 1928, shows that the glacier had retreated from its innermost moraine and had an area of 3.49 km^2 (Table 3). Recession proceeded rapidly until the late 1960s, at which time Overlord Glacier terminated farther upvalley than at any time since the early 1700s. Thereafter, the glacier advanced, reaching a position 120 m farther downvalley by 1980. Since 1980, it has retreated at rates of 7 to 18 m/a, based on positions of annual push moraines. Overlord Glacier is presently inside its late 1960s limit and thus is smaller than it has been at any time in the past 300 years.

4.2. Black Tusk Glacier

Three snowfields and two small cirque glaciers occupy an area of 0.68 km^2 around the Black Tusk, in comparison to 1.12 km^2 in 1928 when the first photographs were taken (Fig. 3). Ice cover in 2005 was about 12% of that at the Little Ice Age maximum, when the cirque glaciers

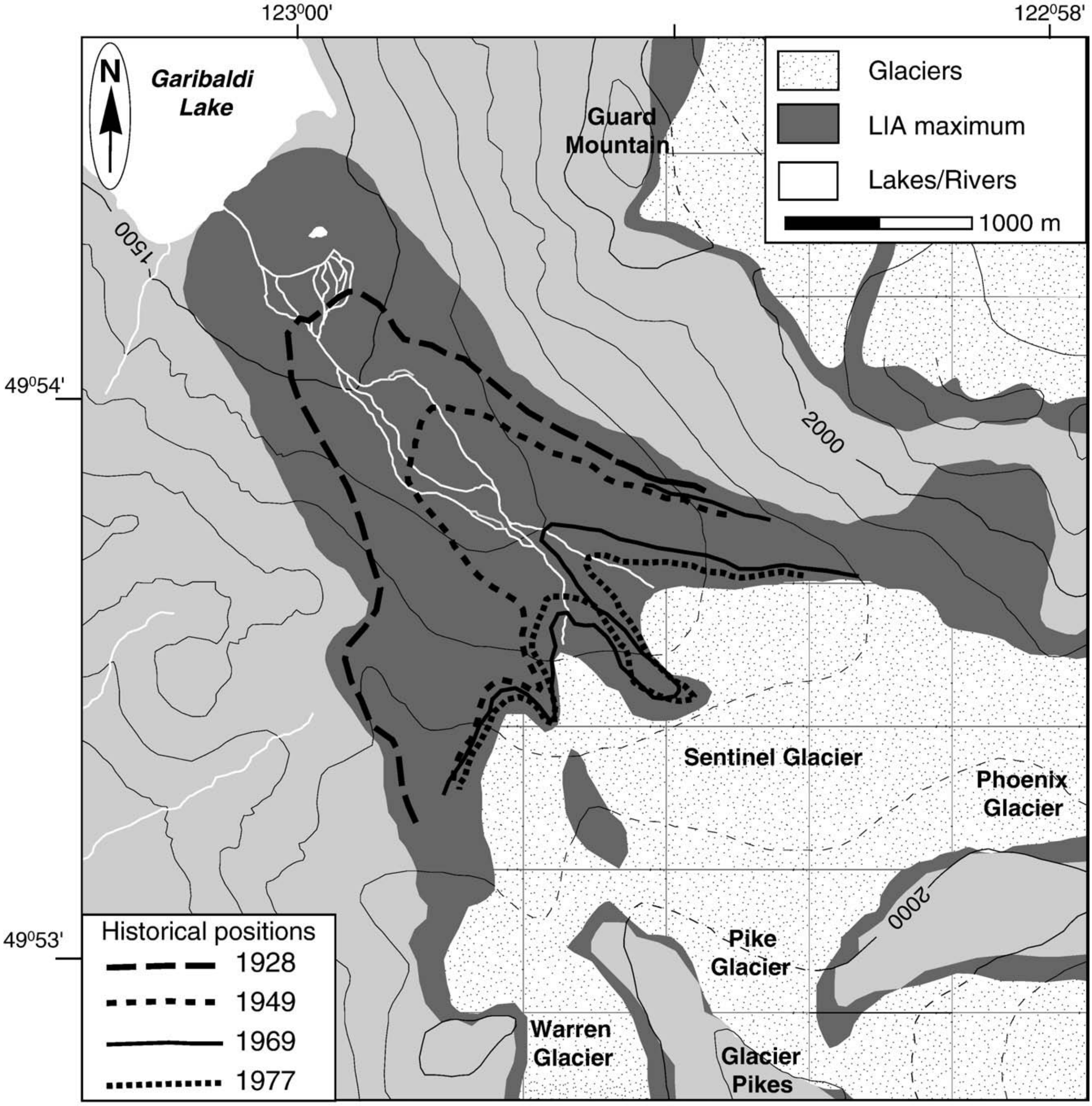

Fig. 7. Map of Sentinel Glacier showing its present and maximum Little Ice Age extents and historic margins.

coalesced (Fig. 3; Table 3). Since 1990, the cirque glaciers and snowfields have been relatively stable, likely due to their location on north-facing slopes where they are shaded by the steep cirque headwalls.

4.3. Helm Glacier

Helm Glacier and three nearby, small ice masses have an area of 0.924 km^2, less than 20% of their maximum Little Ice Age area (4.97 km^2) (Figs. 4 and 5; Table 3). In 1928 the glacier was 4.28 km^2 in area and its terminus was close to its Little Ice Age limit, thus most of the retreat occurred after that date (Table 3). Only two small push moraines occur between the innermost moraine, which, based on dendrochronology, was abandoned in the 1910s (Koch et al., 2007), and the 1928 glacier terminus, suggesting that recession was slow but continuous. Recession continued at an average rate of 15–17 m/a until about 1969, although with considerable annual variability — in 1935 and 1936 the glacier retreated 6.5 m and 34 m, respectively (Taylor, 1936, 1937). Helm Glacier began to advance about 1969, and the advance continued until 1977. Between 1977 and 1990, the west part of the glacier disintegrated into small cirque glaciers. Recession of Helm Glacier has accelerated in the past decade, and cirque glaciers that were formerly confluent with the main glacier lost about half of their area between 1996 and 2003. The terminus of the glacier retreated up to 70 m between 2003 and July 2008, when it was last visited. Ice has been exposed over the entire surface of the glacier in late summer of every year since 2002, and Helm Glacier will disappear by 2050 if present rates of downwasting and retreat continue.

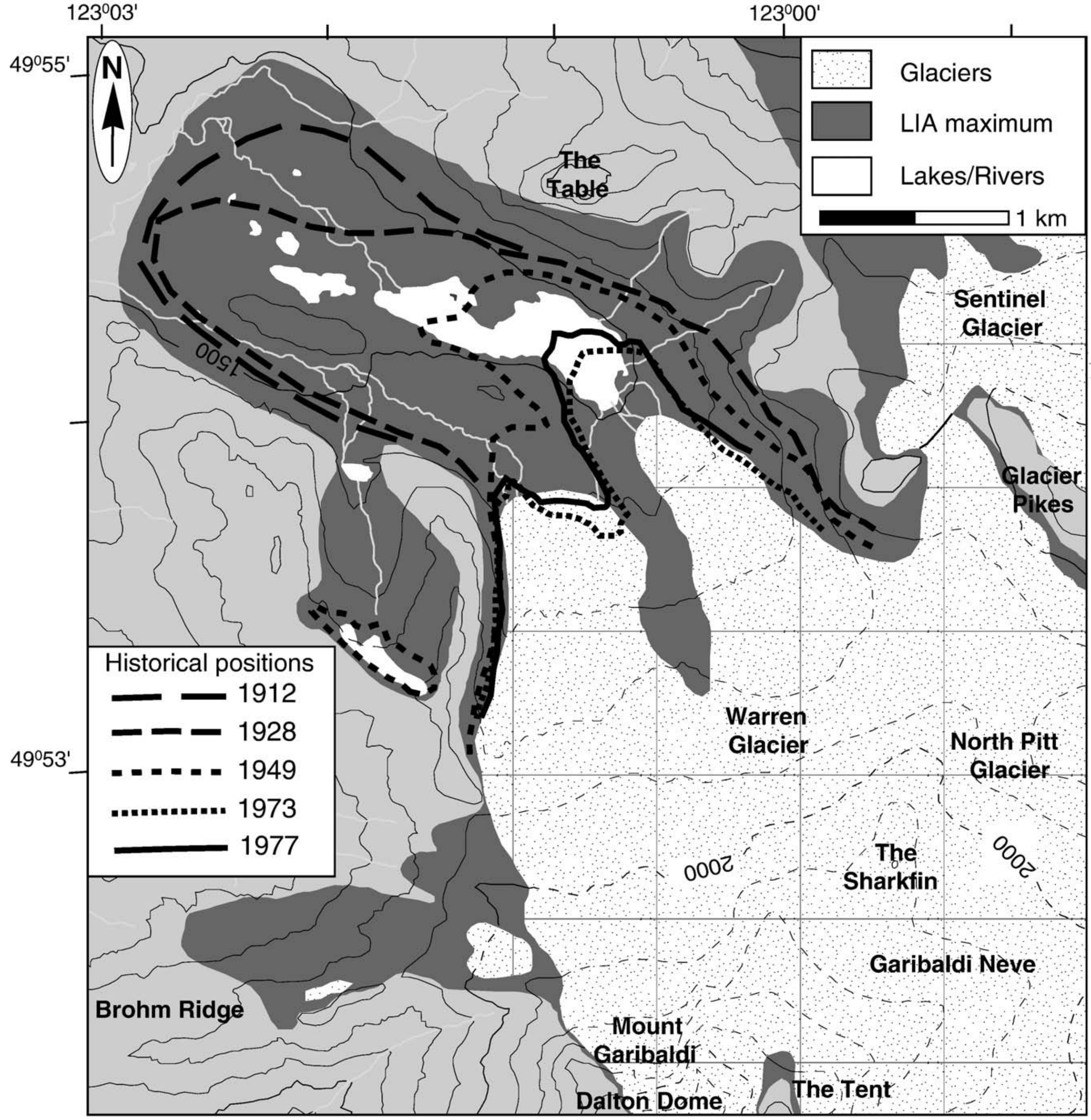

Fig. 8. Map of Warren Glacier showing its present and maximum Little Ice Age extents and historic margins.

4.4. Sphinx Glacier

Sphinx Glacier has lost about 61% of its area since the early 1700s (Fig. 6; Table 3). It abandoned two moraines in the first and second decades of the 20th century, based on tree rings and lichen measurements (Koch et al., 2007). When the glacier was first photographed in 1928, the trunk glacier and the tributary glacier from the south were almost in contact, although the main terminus was 250 m inside the innermost moraine. Retreat continued at varying rates until 1964; in 1935 and 1936, for example, retreat was 12 m and 80 m, respectively (Taylor, 1936, 1937). An advance began between 1964 and 1969 and continued until 1977. Sphinx Glacier has retreated continuously since 1977.

4.5. Sentinel Glacier

Sentinel Glacier comprises three ice tongues with a total area of 2.59 km^2 (Fig. 7; Table 3). Stabilization and abandonment of its two innermost moraines have been dated to the 1910s and 1920s by dendrochronology and lichenometry (Koch et al., 2007). The glacier retreated from the innermost moraine with only short interruptions, but at variable rates; recession in 1935 and 1936 was 73 m and 15 m, respectively (Taylor, 1936, 1937). Mass balance between 1965 and 1974 was positive, yet the terminus retreated an additional 263 m during this period (Mokievsky-Zubok and Stanley, 1976). The three tongues of Sentinel Glacier behaved differently between 1969 and 1977: the west and east tongues retreated, whereas the middle

Fig. 9. Warren Glacier in 1912 (top; W.J. Gray), 1928 (middle; BC Archives I-67560), and 2001 (bottom; J. Koch).

tongue advanced 130 m. A small moraine in front of the east tongue indicates that this part of Sentinel Glacier advanced briefly in the late 1970s or early 1980s. All three snouts have retreated since the late 1970s or early 1980s.

4.6. Warren Glacier

Warren Glacier and its three snowfields have an area of 4.38 km^2 (Table 3). The first photograph of the glacier, taken in 1912, shows the terminus close to a moraine abandoned in the first decade of the 20th century (Figs. 8 and 9; Koch et al., 2007). The west and east halves of Warren Glacier retreated differently, probably because the former is covered by debris. Rates of retreat also varied over the 20th century; in 1935 and 1936 values were 55 m and 17 m, respectively (Taylor, 1936, 1937). Rapid retreat between 1977 and 1982 was most likely caused by calving in a proglacial lake. Warren Glacier advanced 80 m between 1973 and 1977, but has receded since then. The west half of the glacier, however, has remained relatively stable since 1964, and in 2005 the snout was more advanced than it was in 1969.

4.7. Garibaldi Glacier

Garibaldi Glacier is 64% smaller today than at the Little Ice Age maximum (Fig. 10; Table 3) when Garibaldi and Diamond Head

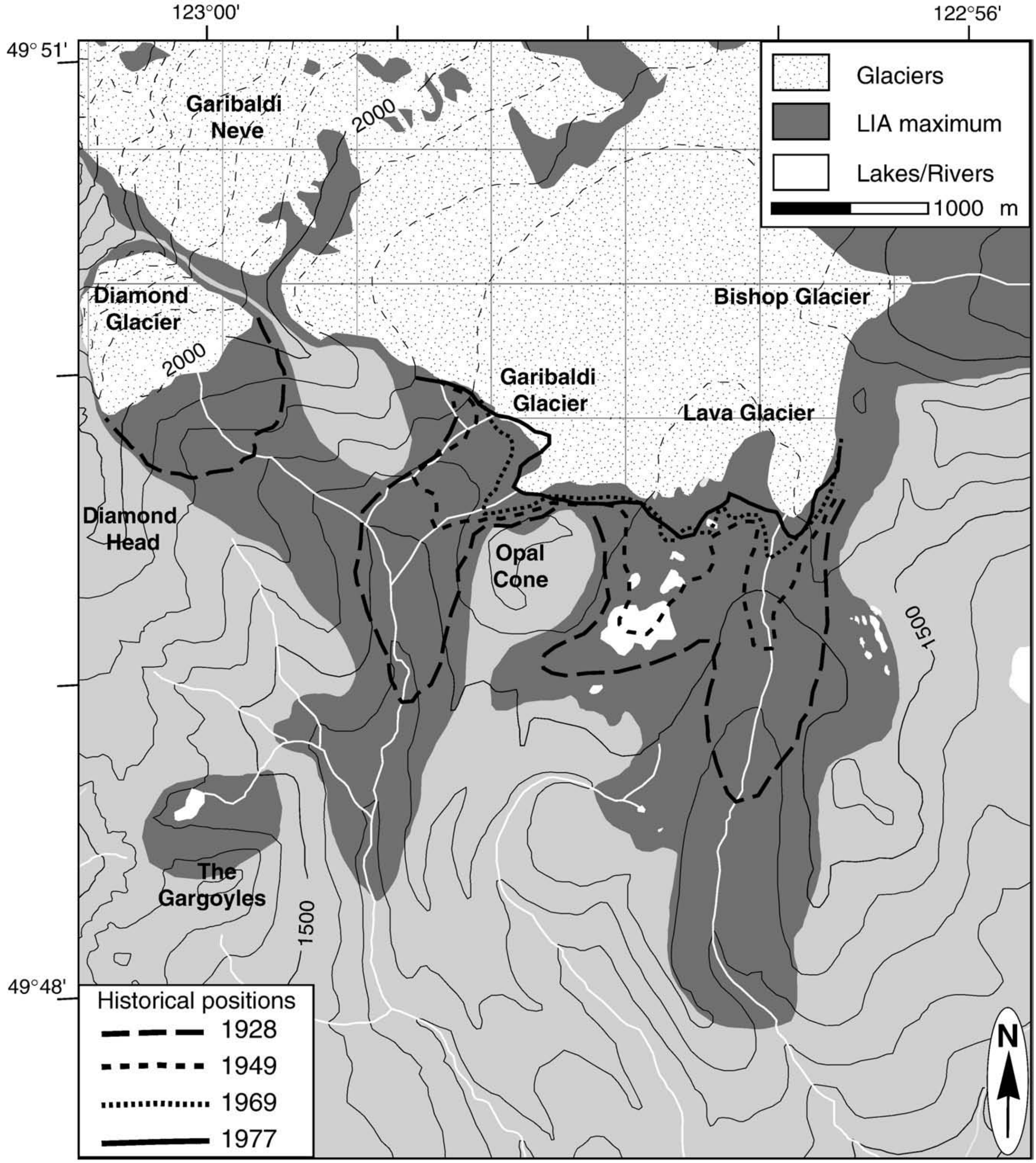

Fig. 10. Map of Garibaldi and Lava glaciers showing their present and maximum Little Ice Age extents and historic margins.

glaciers coalesced. It abandoned its innermost lateral moraine sometime in the 1910s (Koch et al., 2007). In 1928, when the first ground photographs were taken, the glacier was still more than half of its Little Ice Age maximum size. Recession dominated, but at decreasing rates, until 1977. The glacier advanced slightly between 1977 and 1982, and since then has retreated less than 50 m. Garibaldi Glacier ceased to exist as a discrete ice tongue in the late 1970s, thus the small variations since 1982 that are summarized in Table 2 refer to the icefield that feeds it and five other glaciers, including Lava Glacier.

4.8. Lava Glacier

Lava Glacier has an area of 2.57 km^2, about 67% less than at the Little Ice Age maximum (Fig. 10; Table 3). Numerous, undated, small push moraines are present inside the innermost major moraine,

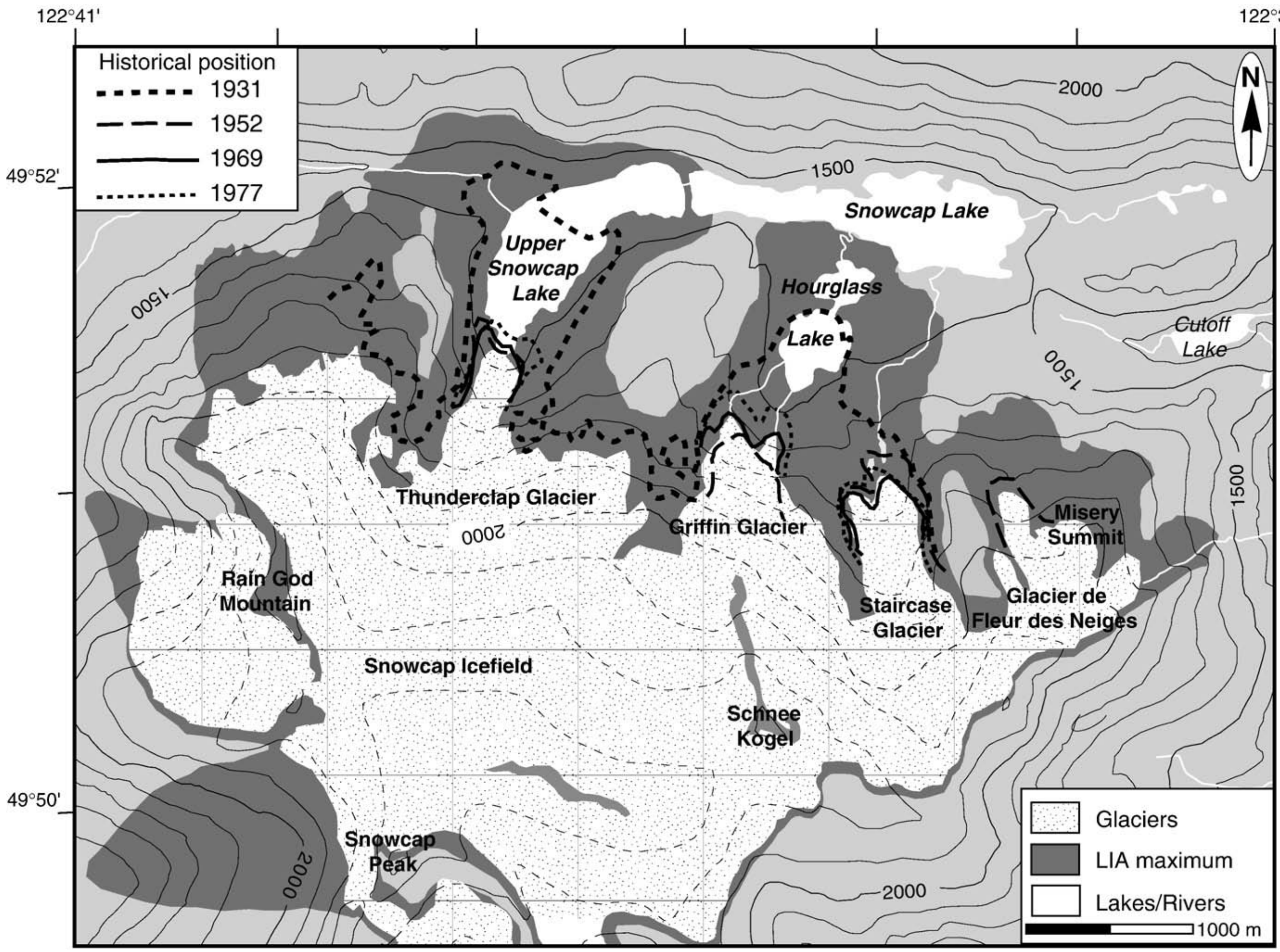

Fig. 11. Map of Snowcap Lakes area showing the present and maximum Little Ice Age extent of glaciers and their historic margins.

which was abandoned in the 1910s (Koch et al., 2007). At the time of the first photograph in 1928, Lava Glacier was nearly two-thirds of its maximum Little Ice Age size and still had two distinct tongues. Both tongues receded at rates of more than 30 m/a until 1969, when the west tongue disappeared. Lava Glacier advanced less than 20 m between 1977 and 1984, but retreated more than 500 m between 1984 and 1996. The latter value is misleading because downwasting of the ice exposed a bedrock knob around which the glacier now flows. The glacier has changed little since 1996.

4.9. Snowcap Lakes area

The four northern outlet glaciers of the Snowcap Icefield presently cover 7.56 km^2, a decrease of 17% since 1987–1988 (Fig. 11; Table 3). In 1931, when the first aerial photographs were taken, Griffin and Staircase glaciers were still confluent and covered the south part of Hourglass Lake. Recession dominated throughout the first half of the century, but Griffin and Thunderclap glaciers began to advance sometime before 1969, and all three glaciers advanced between 1969 and 1977. Griffin and Thunderclap glaciers were still advancing in 1978, with Griffin Glacier overriding living vegetation (Ricker, 1979). Shortly thereafter, however, the three glaciers began to retreat at relatively constant rates. The extent of the three glaciers in 1996 was similar to that in 1969, when the advance began. Between 1996 and 2004, Thunderclap Glacier retreated out of Snowcap Lakes. Glacier de Fleur des Neiges, just east of Staircase Glacier, shows a net loss in length of 120 m between 1952 and 1996, almost entirely after 1978 (Ricker, 1979).

4.10. Stave Glacier

Stave Glacier covers 9.45 km^2 at present (Fig. 12; Table 3). It abandoned its innermost moraine in the first decade of the 20th century (Koch et al., 2007). The glacier occupied only the northern embayment of its proglacial lake in 1952, when the first aerial photographs of the glacier were taken. Sometime between 1969 and 1977, the south tributary lobe ceased to feed the main tongue, leading to rapid recession (an average rate of 53 m/a between 1977 and 1996).

4.11. Glacier thinning and volume losses

Substantial downwasting of the mapped glaciers is revealed by differencing the 1928 and 1987 DEMs (Fig. 13). Glaciers thinned most at their mid-valley positions, which is to be expected because glaciers are thinnest at their margins. Some glaciers appear to have thickened slightly at their highest elevations (Fig. 13). This thickening, however, is probably not real, but rather the result of poor contrast in the photographs used to create either the 1928 topographic map or the TRIM DEM. Errors originating from poor photographic contrast have been previously reported for TRIM data for small glaciers and snowfields at high elevations (Schiefer et al., 2007). Vertical changes

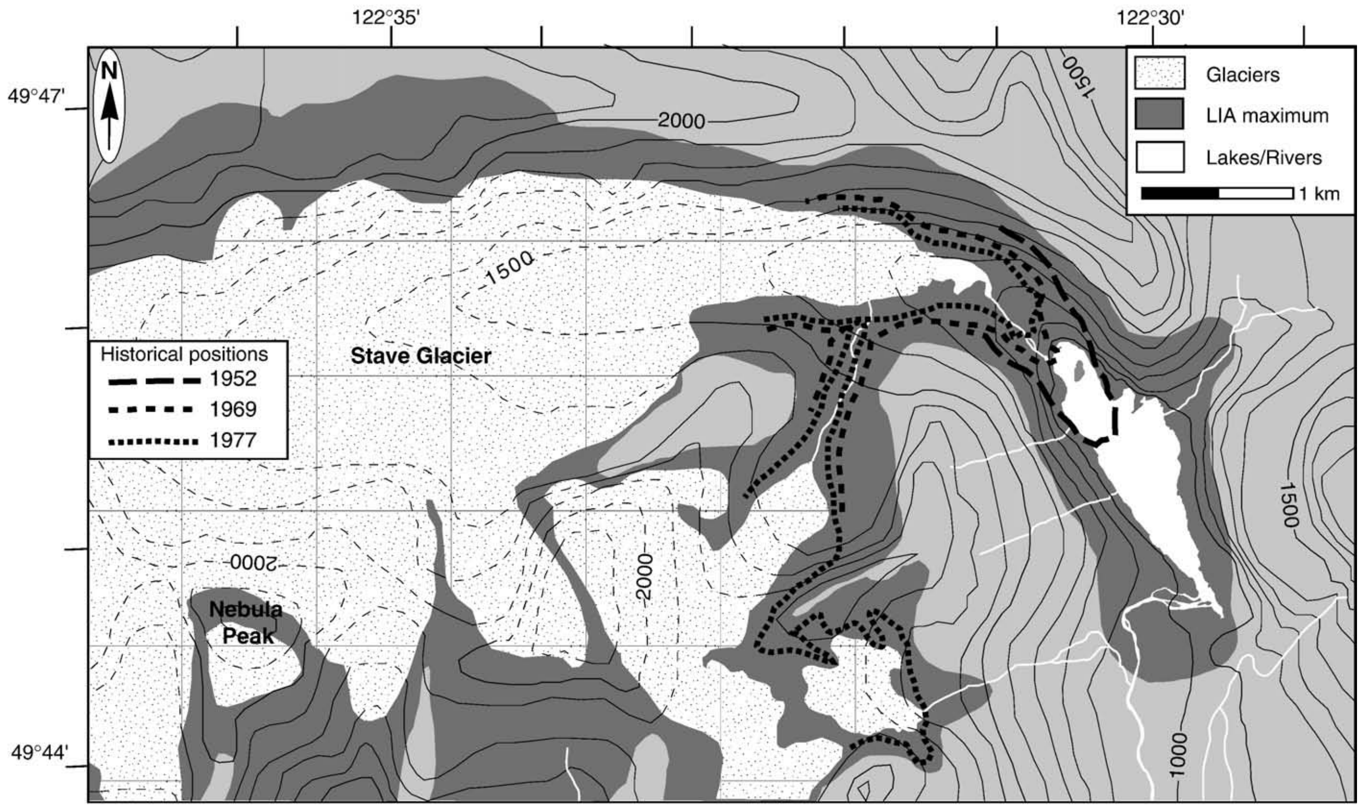

Fig. 12. Map of Stave Glacier showing its present and maximum Little Ice Age extents and historic margins.

in areas of steep ice and along the edges of some glaciers near the boundary of the 1928 map may arise from errors in co-registering the DEMs.

Large glaciers near Mt. Garibaldi substantially thinned between 1928 and 1987 (Fig. 14). Glacier-averaged lowering in surface elevation are, for example, 47 m for Warren Glacier, 17 m for Bishop-Lava glaciers, 49 m for Sentinel Glacier, 48 m for Sphinx Glacier, and 58 m for Helm Glacier (Table 4).

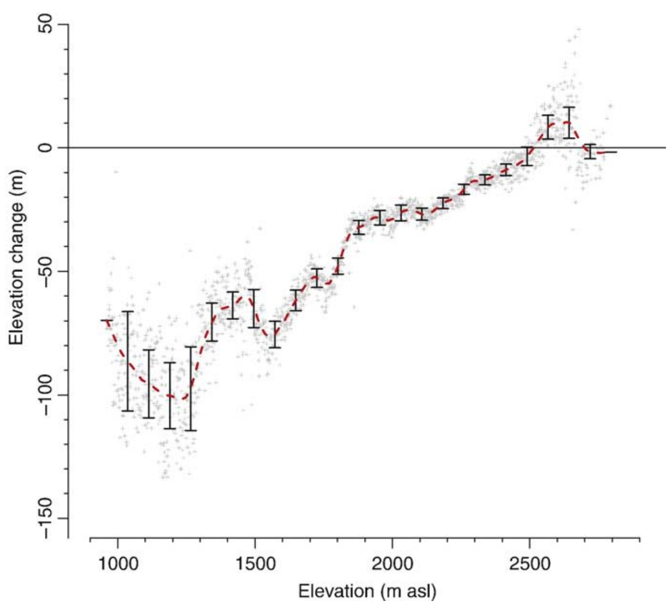

Fig. 13. Elevation change vs. altitude over glacierized terrain in Garibaldi Park for the period 1928–1987. The red line shows the smoothed record (curve with 5% window). The vertical bars are standard errors based on sample number and standard deviation of elevation change. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The 158 km^2 of glaciers in Garibaldi Park in 1987 thinned 32 m on average. This downwasting translates into a volume loss of 5.40 ± 2.42 km^3 (Table 4). The area of glacier ice shown on the 1928 map is 38% of the ice cover in 1987, thus we estimate the total ice loss in the park between 1928 and 1987 to be about 14.2 ± 6.4 km^3.

5. Discussion

At the beginning of the 20th century, glaciers in Garibaldi Park terminated near their Little Ice Age limits. They retreated slowly during the first two decades of the 20th century, interrupted by small advances or still-stands during which moraines were built and later abandoned (Tables 2 and 5). The youngest moraines date to the 1920s (Koch et al., 2007). Glaciers rapidly retreated between the 1920s and 1960s (Fig. 15; Tables 2 and 5), and Overlord and Griffin glaciers were smaller in the 1960s than at any earlier time in the late Holocene. Glaciers advanced up to 300 m between the 1960s and early 1980s, followed by retreat that has continued to the present (Fig. 15; Tables 2 and 5). Today, most glaciers are positioned upvalley of their 1960s limits.

Glaciers in Garibaldi Park have behaved similarly to those elsewhere in western Canada during the 20th century. Most glaciers in western Canada receded from late 19th century moraines before advancing and constructing moraines in the 1910s to 1920s (Luckman, 2000; Larocque and Smith, 2003; Koch et al., 2007). The next four decades were a time of rapid glacier retreat, with some glaciers receding up to 1800 m (West and Maki, 1961; Menounos et al., 2005). Glaciers were stable or advanced up to 1000 m between the 1950s and early 1980s (Baranowski and Henoch, 1978), but since then have retreated, with length losses of up to 500 m (Kershaw et al., 2005) and

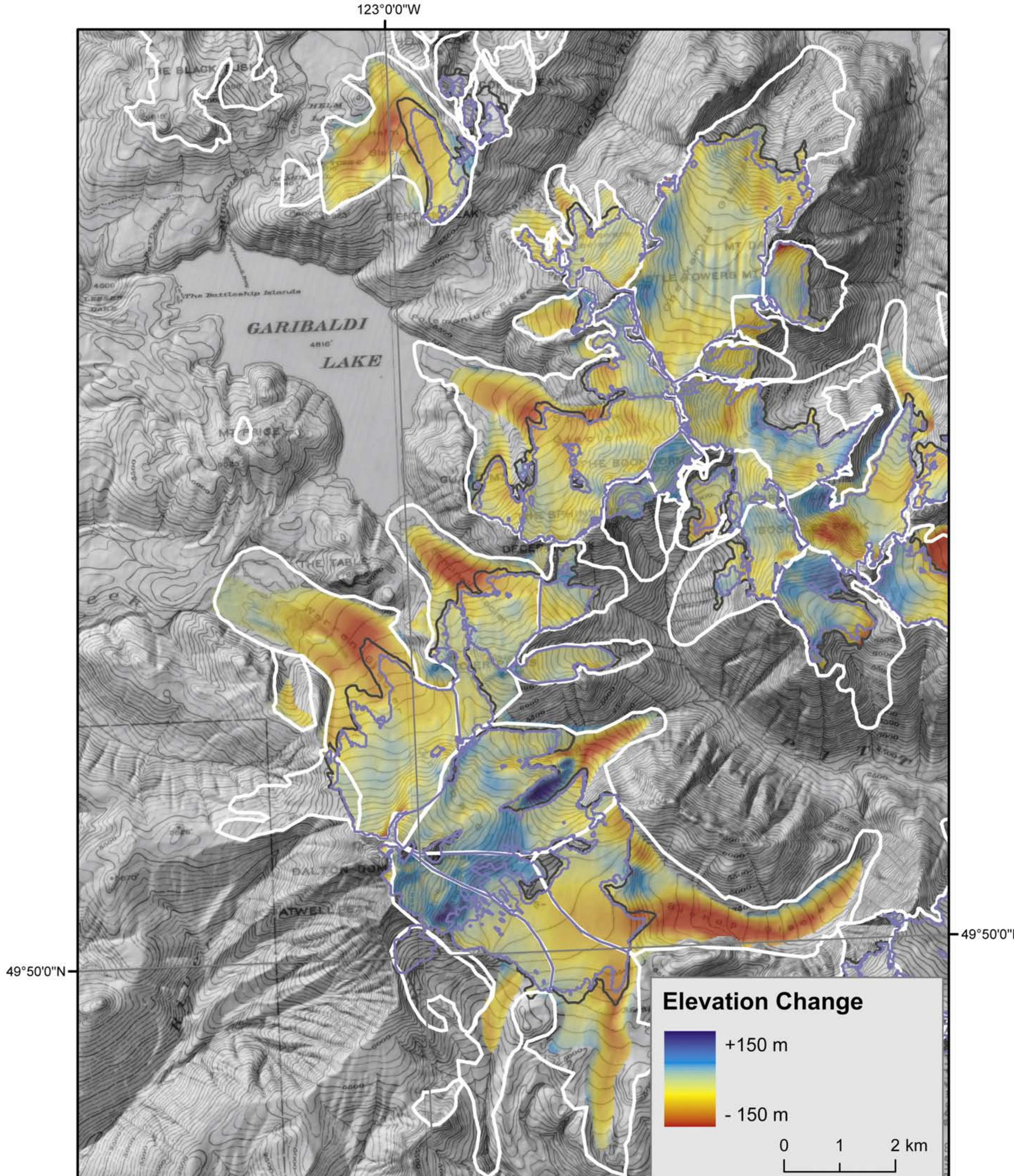

Fig. 14. Observed elevation change of glacier tongues near the Garibaldi Neve. Colours denote elevation loss (red) and gain (blue). Most of the elevation gains are erroneous and result from small positional errors in steep terrain. The base image is the 1928 topographic map with hillshading derived from the 1987 TRIM DEM. Glacier extents during the Little Ice Age, 1987, and 2005 are denoted, respectively, with white, black, and light blue polygons. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Measured elevation and volume change of glaciers in Garibaldi Provincial Park.

Glacier	Area (km^2) 1928	Δ Elevation (m) 1987–1928	Δ Volume (km^3) 1987–1928	Volume error (km^3) 1987–1928	Area (km^2) 1987	Δ Elevation (m) 1999–1987	Δ Volume (km^3) 1999–1987	Volume error (km^3) 1999–1987
Blackholm	0.73	−30	−0.02	0.01	0.58	−9	−0.0053	0.0022
Castle Towers	2.48	−30	−0.07	0.04	1.92	−4	−0.0075	0.0073
Chaos	2.95	16	0.05	0.05	2.81	−7	−0.0186	0.0107
Cheakamus	8.33	−20	−0.16	0.13	7.90	−11	−0.0088	0.03
Curtain	1.06	−32	−0.03	0.02	0.80	−5	−0.0041	0.0031
Diavolo	3.81	−3	−0.01	0.06	3.03	−15	−0.0458	0.0115
Fitzsimmons	2.14	−25	−0.05	0.03	1.60	−11	−0.0173	0.0061
Forger	4.63	−12	−0.05	0.07	3.94	−9	−0.0349	0.015
Helm	4.28	−58	−0.25	0.07	1.28	−11	−0.0138	0.0049
Horstman	0.48	−25	−0.01	0.01	0.34	−11	−0.0036	0.0013
Iago	1.47	−39	−0.06	0.02	0.84	−16	−0.0138	0.0032
Isoceles	4.18	−26	−0.11	0.06	3.26	−10	−0.0316	0.0124
Lava/Bishop	9.19	−17	−0.16	0.14	6.37	−15	−0.0939	0.0242
Macbride	7.61	−59	−0.45	0.12	6.06	−8	−0.0491	0.023
N Pitt	7.87	−4	−0.03	0.12	5.76	−7	−0.04	0.0219
Naden	1.32	4	0.01	0.02	1.14	−10	−0.0113	0.0043
Neal	4.37	−45	−0.2	0.07	3.12	−3	−0.0077	0.0119
Needles	4.73	−9	−0.04	0.07	4.29	−7	−0.0286	0.0163
Overlord	3.49	−23	−0.08	0.05	3.00	−10	−0.0304	0.0114
Phoenix	1.13	−11	−0.01	0.02	0.73	−4	−0.0032	0.0028
Pike	1.08	−6	−0.01	0.02	0.88	−5	−0.0048	0.0033
Ripsaw	0.87	−45	−0.04	0.01	0.74	−10	−0.0076	0.0028
S Pitt	6.39	−68	−0.44	0.1	2.58	−14	−0.0372	0.0098
Sentinel	3.95	−49	−0.19	0.06	2.27	−4	−0.0084	0.0086
Shatter	4.16	−15	−0.06	0.06	3.90	−15	−0.0577	0.0148
Shudder	2.73	−54	−0.15	0.04	2.13	−13	−0.0277	0.0081
Spearhead	2.57	−48	−0.12	0.04	2.15	−14	−0.0293	0.0082
Sphinx	6.09	−48	−0.29	0.09	4.67	−3	−0.0115	0.0177
Tremor	3.22	−18	−0.06	0.05	2.83	−10	−0.0271	0.0107
Trorey	1.86	−54	−0.1	0.03	1.49	−12	−0.0172	0.0057
Ubysseey	5.15	−53	−0.27	0.08	3.90	−7	−0.026	0.0148
Unnamed	3.15	−49	−0.16	0.05	2.39	−7	−0.0158	0.0091
Unnamed	1.02	−94	−0.1	0.02	0.22	−15	−0.0034	0.0008
Unnamed	2.17	−40	−0.09	0.03	0.85	−16	−0.0134	0.0032
Unnamed	0.84	−35	−0.03	0.01	0.61	−4	−0.0022	0.0023
Unnamed	1.12	9	0.01	0.02	0.72	−1	−0.0009	0.0027
Unnamed	3.94	−79	−0.31	0.06	2.64	10	0.0264	0.01
Unnamed	1.15	−40	−0.05	0.02	0.71	2	0.0012	0.0027
Unnamed	0.72	−36	−0.03	0.01	0.17	−3	−0.0005	0.0007
Unnamed	1.69	−10	−0.02	0.03	1.41	3	0.0038	0.0054
Unnamed	2.20	−13	−0.03	0.03	1.56	−8	−0.0127	0.0059
Unnamed	0.95	−20	−0.02	0.01	0.94	−6	−0.0057	0.0036
Warren	9.68	−47	−0.45	0.15	5.23	−12	−0.0616	0.0199
Weart	11.31	−48	−0.54	0.17	10.17	−13	−0.1361	0.0386
Wedgemount	3.64	−27	−0.1	0.06	1.95	−11	−0.0219	0.0074
	157.86	−31.93	−5.38	2.43	115.89	−8.20	−1.05	0.44

Note: The 1987–1999 elevation change values are from bias-corrected SRTM data (Schiefer et al., 2007).

average thinning rates of about 0.53–0.89 m/a (Schiefer et al., 2007). Total loss in ice cover since the Little Ice Age differs from glacier to glacier, with reported values ranging from 10 to 90% (McCarthy and Smith, 1994; Luckman, 1998; Lewis and Smith, 2004a).

Between 1928 and 1987, volumetric loss of the 45 glaciers examined in this study was five times that between 1987 and 1999 (Table 5). Changes in ice volume for the more recent period were derived by differencing of the TRIM DEM and a DEM derived from

Table 5
Summary of fluctuations of glaciers in Garibaldi Provincial Park during the twentieth century.

Glacier	Decade 0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–00
Overlord	r/s	r/s	m	r	r	r/a	a	a/r	r	r
Helm	r/s	m	r	r	r	r/a	a	r	r	r
Sphinx	m	m	r	r	r	r	r/a	a	r	r
Sentinel	m	m	r	r	r	r	r	r/a	a/r	r
Warren	m	r	r	r	r	r	r	r/a	r	r
Garibaldi	r/s	m	r	r	r	r	r	r/a	a/r	r
Lava	r/s	m	r	r	r	r	r	r	r	r
Thunderclap	?	?	r	r	r	r	a	a	a/r	r
Griffin	m	m	r	r	r	r	a	a	a/r	r
Staircase	?	?	r	r	r	r	r	a	r	r
Stave	m	r	r	r	r	r	r	r	r	r

Notes: r: retreat; s: stable; m: moraine stabilization; a: advance. Dominant behaviour is underlined.

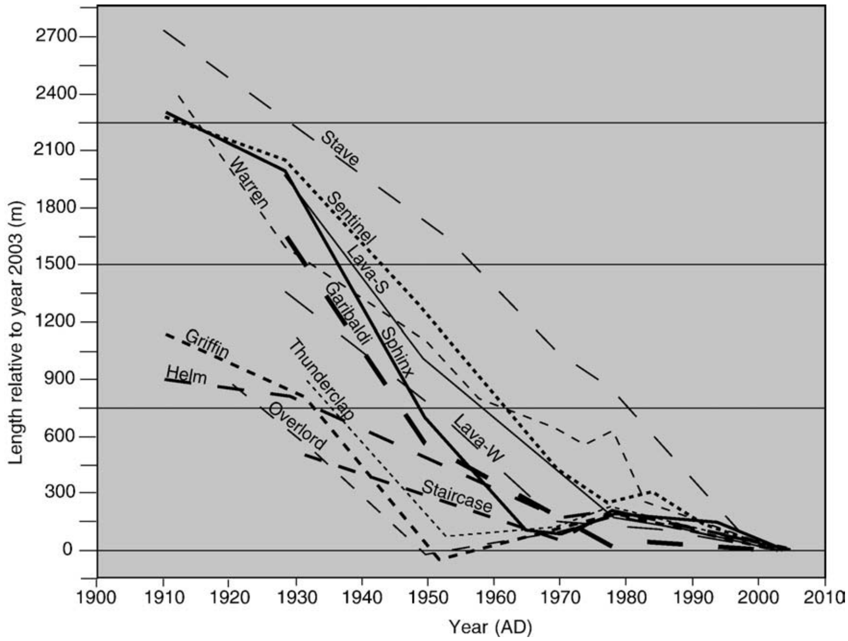

Fig. 15. Comparison of average retreat rates of glaciers in Garibaldi Park in the 20th century. Zero corresponds to glacier extent in 2002–2004 when fieldwork was done for this study.

Shuttle Radar Topographic Mission (SRTM) data (Schiefer et al., 2007). Average thinning rates are 0.68 m/a for the period 1987–1999, compared to 0.54 m/a for the period 1928–1987.

We explored the relation between climate variability and glacier extent and volume in Garibaldi Park by examining monthly mean temperature and precipitation data from the Agassiz CDA (Canada Department of Agriculture) climate station (Fig. 1). We used the Agassiz record because, as pointed out by Moore and Demuth (2001), it is less affected by urban development than records from other climate stations in the region.

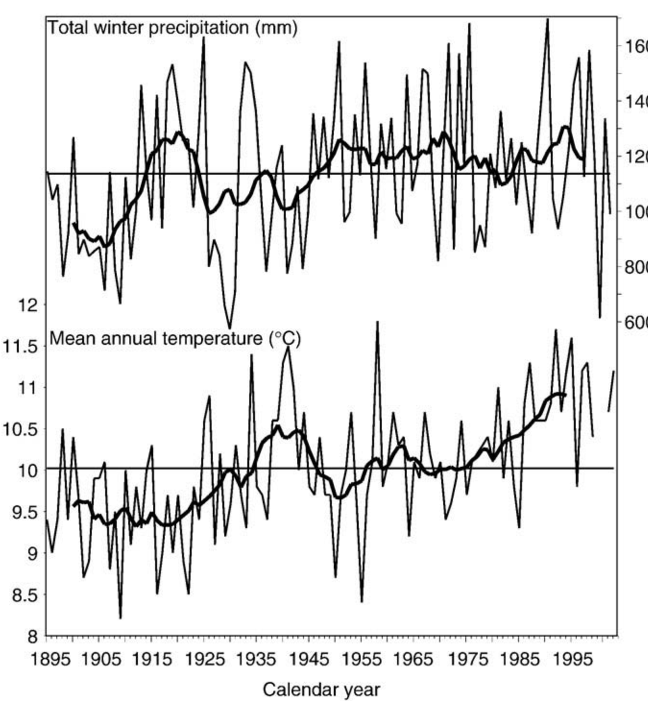

Fig. 16. Total winter precipitation and mean annual temperature at Agassiz (A in Fig. 1). The horizontal lines are the averages for the complete record, and bold lines are 10-year running means.

The Agassiz climate data (Fig. 16) show below-normal mean annual temperatures between 1895 and 1934, 1947 and 1956, and 1967 and 1975, and above-normal temperatures between 1935 and 1947, 1957 and 1966, and since 1975. Total annual precipitation and total winter (October–March) precipitation are lower than normal between 1895 and 1914, and between 1925 and 1946, but higher than normal between 1915 and 1924, and since 1947. The data show that the periods of glacier advance documented in this study are generally cool with variable precipitation, whereas periods of glacier recession are generally warm with variable precipitation, indicating an overall strong dependence on temperature. Our findings also indicate a 5–10 year lag in the frontal response of the glaciers to a change in climate, consistent with previous work in the Pacific Northwest (Kovanen, 2003).

A detailed comparison of the relation between climate and the volume of glacier ice in Garibaldi Park is not possible because of the small number of available DEMs. However, lower thinning rates between 1928 and 1987 than between 1987 and 1999 may result from the occurrence of both warm and cool decades during the earlier period. We plan to generate additional DEMs for many of the glaciers in Garibaldi Park from aerial photographs dating from 1946 to the present. These additional DEMs will allow us to compare climate and the volumetric response of glaciers at a decadal time scale.

Glacier behaviour in northwest North America is also linked to the Pacific Decadal Oscillation (PDO), a coupled ocean–atmospheric phenomenon that influences temperature and precipitation variability in the Pacific Northwest and in western Canada (McCabe and Fountain, 1995; Mantua et al., 1997; Hodge et al., 1998; Bitz and Battisti, 1999; Gedalof and Smith, 2001; Moore and Demuth, 2001; Mantua and Hare, 2002; Menounos, 2002; Kovanen, 2003; Lewis and Smith, 2004b). The PDO is a long-lived, El Niño-like pattern of climate variability characterized by alternating states of higher and lower sea surface temperatures in the North Pacific (Zhang et al., 1997; Mantua and Hare, 2002). During the positive phase of the PDO, an enhanced Aleutian Low reduces storminess in the Pacific Northwest. Storm tracks divert towards Alaska, resulting in warmer and drier winters in

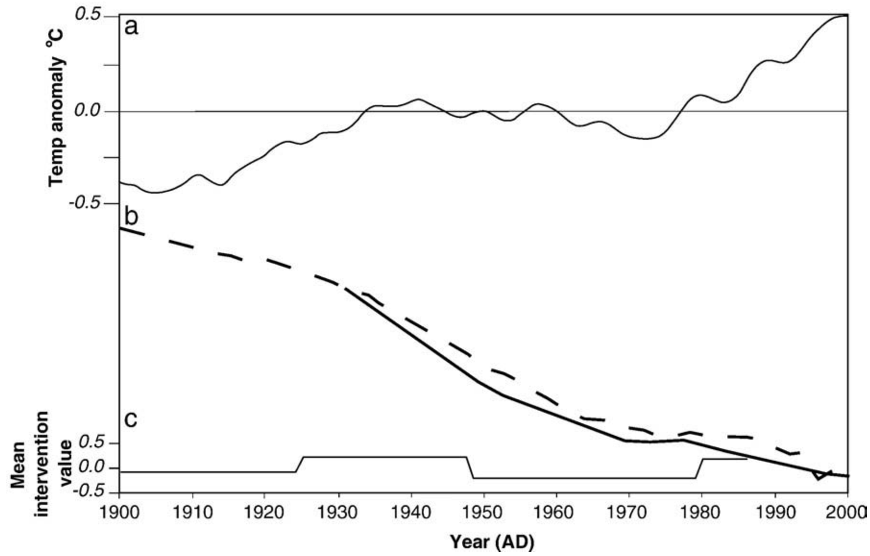

Fig. 17. (a) Global temperature average since AD 1900 using a combined land and marine dataset (HadCRUT2v; Jones and Moberg, 2003). (b) Relative glacier extent based on a network of glaciers around the world (stippled line; Oerlemans, 2005) and Garibaldi Park (solid line; this study). (c) Mean intervention values for the Pacific Decadal Oscillation (Gedalof and Smith, 2001).

southern British Columbia, with below-average snow packs and negative winter glacier mass balances. Conversely, during the negative phase of the PDO, a diminished Aleutian Low causes increased winter storminess in the Pacific Northwest. Storm tracks divert away from Alaska, leading to lower air temperatures, higher precipitation, and greater snow depth in southern British Columbia. Positive PDO phases between 1925 and 1946 and since 1977 are times of glacier recession in Garibaldi Park, and negative PDO phases between 1890 and 1924 and between 1947 and 1976 coincide with intervals of stable or advancing glaciers (Fig. 17).

The PDO, however, may not be totally responsible for glacier fluctuations in Garibaldi Park during the past century. Glaciers in most parts of the world have fluctuated in a similar manner to those in Garibaldi Park (Fig. 17; Koch and Clague, 2005; Oerlemans, 2005), suggesting that the forcing mechanisms are operating on a global scale. Alpine glaciers in the Americas, Europe, Asia, and New Zealand have receded since the Little Ice Age (Arendt et al., 2002; Rignot et al., 2003; Paul et al., 2004), and the rate of recession in the late 20th century appears anomalous in the context of the Holocene (Reichert et al., 2002). The instrumental record of global temperatures shows that warming in the 20th century occurred during two phases: 1920–1940 and 1975 until the end of the century (Fig. 17; Bradley and Jones, 1993; Jones et al., 1999; Jones and Moberg, 2003). The two intervals coincide with periods of global glacier recession (New Zealand Alps: Gellatly et al., 1988; western U.S.: Harper, 1993; Alaska: Evison et al., 1996; Patagonian Andes: Aniya, 2001; European Alps: Holzhauser and Zumbühl, 2002; tropical Andes: Georges, 2004; Spanish Pyrenees: Cía et al., 2005; Antarctic Peninsula: Cook et al., 2005; western Canada: Koch and Clague, 2005). The intervening period coincides with glacier advances in Garibaldi Park and the above-mentioned areas.

Observed historical ice loss in Garibaldi Park and in mountain regions around the world is broadly synchronous and attributable to global 20th century climate warming (Fig. 17). If warming continues, glaciers in Garibaldi Park will become smaller and may vanish, which will be detrimental to recreation and tourism. Glaciers are important for summer skiing at Whistler resort, just outside the park (Fig. 1), and are a major attraction for outdoor enthusiasts. Glacier loss will negatively affect hydroelectric power generation, agriculture, and salmon runs in the Pacific Northwest, because streams during late summer, which are presently dominated by glacier melt, will carry less water (Stahl and Moore, 2006).

6. Conclusions

Glaciers in Garibaldi Park fluctuated synchronously in the 20th century. Still-stands and minor readvances during the first two decades of the century punctuated slow retreat. Glacier recession was particularly pronounced between the 1930s and 1960s and since the 1980s. Between these periods, glaciers advanced up to 300 m or were stable. The total area of ice cover in the park has decreased by about 260 km^2 since the Little Ice Age maximum in the late 17th or early 18th century, a 51% loss in about 300 years. However, the majority of this loss occurred in the early 20th century. At present, about 13% (245 km^2) of Garibaldi Park is still ice-covered, but glaciers are rapidly retreating and some may vanish by the end of the century if the present trend continues.

Periods of glacier recession coincide with warm and relatively dry periods, as well as with positive PDO phases, whereas advances occurred during relatively cold periods and negative PDO phases. However, glacier behaviour in Garibaldi Park is also broadly synchronous with that elsewhere in the Northern and Southern Hemispheres, suggesting a common, global climatic cause. We conclude that global temperature change in the 20th century explains much of the behaviour of glaciers in Garibaldi Park and elsewhere.

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