The most direct evidence of pre-'Little Ice Age' glacier activity is found in glacier forefields and includes in situ tree stumps (Ryder and Thomson, 1986; Luckman et al., 1993; Wiles et al., 1999; Wood and Smith, 2004), detrital logs and branches (Ryder and Thomson, 1986; Luckman et al., 1993; Wiles et al., 1999), and organic soils and detrital wood exposed in composite lateral moraines (Röthlisberger, 1986; Osborn et al., 2001; Reyes and Clague, 2004). Here, we present a detailed study of Holocene glacier fluctuations prior to the 'Little Ice Age' in Garibaldi Provincial Park in the southern Coast Mountains of British Columbia (Figure 1) based on such evidence. Our objectives are to: (1) summarize new data from Garibaldi Park; (2) compare the record from the park with other records of Holocene glacier activity in western Canada; and (3) discuss the likely climate forcing mechanisms. Evidence for 'Little Ice Age' and twentieth-century glacier fluctuations in the park is presented elsewhere and is not discussed further here (Koch et al., 2007).

Study area

Garibaldi Provincial Park is located in the southern Coast Mountains about 70 km north of Vancouver, British Columbia (Figure 1). The park contains more than 150 glaciers, which are

---

**Pre-‘Little Ice Age’ glacier fluctuations in Garibaldi Provincial Park, Coast Mountains, British Columbia, Canada**

Johannes Koch, * Gerald D. Osborn and John J. Clague

(1Department of Earth Sciences, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada; 2Department of Geology and Geophysics, University of Calgary, Calgary, Alberta T2N 1N4, Canada)

Received 21 July 2006; revised manuscript accepted 10 June 2007

Abstract: Holocene glacier fluctuations prior to the ‘Little Ice Age’ in Garibaldi Provincial Park in the British Columbia Coast Mountains were reconstructed from geomorphic mapping and radiocarbon ages on 37 samples of growth-position and detrital wood from glacier forefields. Glaciers in Garibaldi Park were smaller than at present in the early Holocene, although some evidence exists for minor, short-lived advances at this time. The first well-documented advance dates to 7700–7300 14C yr BP. Subsequent advances date to 6400–5100, 4300, 4100–2900 and 1600–1100 14C yr BP. Some glaciers approached their maximum Holocene limits several times during the past 10 000 years. Periods of advance in Garibaldi Park are broadly synchronous with advances elsewhere in the Canadian Cordillera, suggesting a common climatic cause. The Garibaldi Park glacier record is also broadly synchronous with the record of Holocene sunspot numbers, supporting previous research that suggests solar activity may be an important climate forcing mechanism.

Key words: Glacier advances, dendroglaciology, Holocene, solar forcing, Garibaldi Park, Coast Mountains, British Columbia.

Introduction

Recent studies point to significant and rapid fluctuations of climate throughout the Holocene (Bond et al., 2001; Mayewski et al., 2004). Alpine glaciers have long been used to document these fluctuations (Denton and Karlén, 1973), because they respond rapidly to changes in their mass balance and thus to changes in temperature and precipitation. Unfortunately, most studies of past glacier fluctuations allow reconstruction of climate variability only on centennial and decadal timescales. Furthermore, many studies of Holocene glacier fluctuations suffer from the fact that glacier advances in the Northern Hemisphere during the past millennium (‘Little Ice Age’) were the most extensive of the Holocene and obliterated or obscured most of the evidence of previous advances. Pre-‘Little Ice Age’ moraines are rare in western Canada and their ages are generally not well constrained (Osborn, 1985; Ryder and Thomson, 1986; Osborn and Karlstrom, 1988; Osborn and Gerloff, 1996; Larocque and Smith, 2003). Sediments in lakes downvalley of glaciers can provide a more complete record of Holocene glacial activity (Leonard, 1986a, b; Desloges and Gilbert, 1995; Leonard and Reasoner, 1999; Menounos et al., 2004), but the record commonly is complicated by non-climatic factors.

© 2007 SAGE Publications

*Author for correspondence (e-mail: jkoch@sfu.ca)
among the southernmost glaciers in the Coast Mountains. The total area of ice cover in the park is about 390 km².

The landscape of Garibaldi Park has been shaped by Quaternary continental and alpine glaciation and locally by Quaternary volcanism (Mathews, 1958). The park is underlain mainly by granitic rocks of the Coast Plutonic Complex and Cretaceous metasedimentary and volcanic rocks of the Gambier Group (Monger and Journeay, 1994). The southwestern part of the park is dominated by rocks of the Plio-Pleistocene Mount Garibaldi volcanic complex (Mathews, 1958).

The northwest-trending Coast Mountains form an orographic barrier to moisture-laden air flowing from the Pacific Ocean, thus there is a strong west–east environmental gradient across Garibaldi Park. Climate is maritime in the southwestern part of the park but becomes increasingly continental to the north and east. Average annual precipitation at Squamish, at the head of Howe Sound, is 2370 mm, but it is only 1230 mm at Whistler, 60 km to the north. Overall, climate is humid and cool, with very wet winters and dry summers.

The study area is located in the Mountain Hemlock biogeoclimatic zone, which is characterized by long, cool, wet winters and short, cool summers (Brooke et al., 1970). The growing season is short because of heavy snowfall in winter. Arboreal vegetation in forefields investigated in this study is dominated by mountain hemlock (Tsuga mertensiana) and subalpine fir (Abies lasiocarpa), but locally includes Engelmann spruce (Picea engelmannii), whitebark pine (Pinus albicaulis) and yellow cedar (Chamaecyparis nootkatensis).

**Methods**

Glacier forefields were visited in 2002, 2003 and 2004 and systematically searched for detrital and *in situ* fossil wood. Discs were cut from fossil wood found in lateral and end moraines and at the surface. They were air dried and prepared for analysis by sanding with progressively finer grades of sandpaper to enhance the definition and contrast of annual tree-ring boundaries. Tree rings were
measured on a Veltsch stage with a precision of ± 0.001 mm using the software MeasureJ2X. Two to four radii were measured to replicate data and reduce the possibility of missing rings or false rings (Stokes and Smiley, 1968). Floating chronologies were developed for sites where more than one tree was sampled. They were then cross-dated (50-yr dated segments lagged by 25 years, with a critical level of correlation (99%) set at 0.32) to create master ring-width chronologies (Holmes, 1983). Floating chronologies that could not be crossdated with living trees were radiocarbon dated. Standard radiocarbon ages on outer rings were calibrated using the program CALIB 5.0 (Stuiver et al., 2005). Calibrated ages, shown in brackets in this paper, are 1σ ranges.

Interpretation of radiocarbon ages from glacier forefields requires consideration of the provenance and location of the dated material (Osborn, 1986; Röthlisberger, 1986; Ryder and Thomson, 1986; Luckman, 1998). Stumps in growth position in Garibaldi Park show evidence of having been sheared off by glaciers. Bark is commonly preserved as a result of burial of the stumps in sediment. Detrital wood in glacier forefields shows evidence of glacial transport, including missing bark, abrasion, embedded sediment and flattening. This wood is interpreted to have been eroded from in situ trees by glaciers and transported at basal and englacial positions within the glaciers. Preservation of bark or relatively small branches or roots is interpreted to indicate short transport. Only samples in

<table>
<thead>
<tr>
<th>Glacier</th>
<th>Site</th>
<th>Laboratory no.</th>
<th>Cal. yr BP</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wedgemount</td>
<td>Beta-170671</td>
<td>8650±0.60</td>
<td>9540–9630</td>
<td>branch; 90 m from snout</td>
</tr>
<tr>
<td>Spearhead</td>
<td>Beta-157268</td>
<td>3900±80</td>
<td>4230–4430</td>
<td>branch; near snout</td>
</tr>
<tr>
<td>Decker</td>
<td>Beta-168423</td>
<td>3900±60</td>
<td>4280–4420</td>
<td>branch; near snout</td>
</tr>
<tr>
<td>Overlord</td>
<td>ovgl-b</td>
<td>Beta-170665</td>
<td>6170±70</td>
<td>6980–7160</td>
</tr>
<tr>
<td>Helm</td>
<td>hegl-a</td>
<td>Beta-168430</td>
<td>8900±60</td>
<td>9920–10100</td>
</tr>
<tr>
<td>Sentinel</td>
<td>segl-c</td>
<td>Beta-148787</td>
<td>7720±70</td>
<td>8430–8550</td>
</tr>
<tr>
<td>Warren</td>
<td>wagl-d</td>
<td>Beta-148789</td>
<td>6360±80</td>
<td>7250–7340</td>
</tr>
<tr>
<td>Lava</td>
<td>lagl-a</td>
<td>Beta-168426</td>
<td>6170±60</td>
<td>7000–7160</td>
</tr>
<tr>
<td>West Stave</td>
<td>wsyl-a</td>
<td>Beta-170668</td>
<td>1080±60</td>
<td>930–1010</td>
</tr>
<tr>
<td>Stave</td>
<td>stgl-a</td>
<td>Beta-171096</td>
<td>6250±70</td>
<td>7150–7260</td>
</tr>
</tbody>
</table>

**Table 1** Pre ‘Little Ice Age’ radiocarbon ages in Garibaldi Park

Note: Dated samples are outer-perimeter wood comprising less than 25 rings.

© 2007 SAGE Publications. All rights reserved. Not for commercial use or unauthorized distribution.
growth position provide unequivocal evidence for glacier advance and extent at a given time. Detrital wood in a stratigraphic context, such as a lateral moraine or till in a glacier forefield, provides a maximum age for the advance. It also defines the minimum extent of the glacier, because the glacier must have reached at least as far as the wood and probably farther. The possibility must be considered that detrital wood within till could have avalanched into the forefield or died of old age, but in such cases the wood nevertheless still provides a maximum age for the advance. If tree-ring or radiocarbon ages on detrital wood in one glacier forefield are similar to those in other forefields, it is unlikely that the samples were introduced by avalanches or died of old age.

Results

Early-Holocene activity

Detrital wood in three glacier forefields in Garibaldi Park suggests that glaciers were generally less extensive in the early Holocene than in 2002–2004, but that they may have advanced on several occasions to near present-day glacier margins. A large, abraded and partially buried log about 140 m from the 1997 snout of Helm Glacier yielded a radiocarbon age of 8900 ± 60 14C years BP (9920–10 090 cal. yr BP; Table 1). A split and frayed fragment of detrital wood, likely the remains of a small conifer trunk, recovered from the top of a bedrock knob about 90 m from the 2002 margin of Wedgemount Glacier gave an age of 8650 ± 60 14C years BP (9540–9630 cal. yr BP). A shredded stick found on a bar of a meltwater stream about 250 m from the 2000 snout of Warren Glacier (site a in Figure 2) yielded an age of 8050 ± 60 14C years BP (8950–9030 cal. yr BP).

Advance between 7700 and 7300 14C yr BP (8500–8100 cal. yr BP)

Evidence was found in two glacier forefields for a small advance at the time of the ‘8.2 ka event’, an abrupt cooling event most likely caused by a massive discharge of freshwater into the North Atlantic around 8470 cal. yr BP (Alley and Ágústsdóttir, 2005). Two small, shattered and partially buried fragments of coniferous wood were found about 100 m from the 2002 snout of Sphinx Glacier in the 1970s (7640±80 14C yr BP (8380–8480 cal. yr BP); Lowdon and Blake, 1975). The locations of both samples indicate that, prior to the event, Sphinx Glacier was less extensive than at present. Three small pieces of detrital wood 50–400 m from the snout of Sentinel Glacier gave ages of 7720 ± 70 14C years BP (8430–8550 cal. yr BP), 7470 ± 80 14C years BP (8280–8360 cal. yr BP) and 7380 ± 80 14C years BP (8160–8330 cal. yr BP; Menounos et al., 2004). Sentinel Glacier was less extensive at the time of this inferred advance than today. Neither Sphinx nor Sentinel glaciers advanced far beyond their present limit during the 8.2 ka event.

Advances between 6400 and 5100 14C yr BP (7300–5800 cal. yr BP)

Evidence for one or more glacier advances during this period was found in six glacier forefields in Garibaldi Park, showing the regional significance of the event. A degraded, detrital stump recovered from till about 800 m from the 2002 snout of Stave Glacier gave a radiocarbon age of 6250 ± 70 14C years BP (7150–7260 cal. yr BP), indicating that the glacier was more extensive at that time than today. Surface detrital wood 40–200 m from the 2002 snout of Overlord Glacier gave ages of 6170±70 14C yr BP (6980–7160 cal. yr BP) and 5890±70 14C yr BP (6630–6800 cal. yr BP). A third sample, embedded in till 40 m farther downstream, yielded an age of 5980±70 14C yr BP (6730–6910 cal. yr BP). The locations of the three samples indicate that Overlord Glacier was probably less extensive than today prior to this event and advanced into mature forest around 6000 14C yr BP. One of the dated samples
crossdated with two other pieces of detrital wood, providing a floating chronology (Table 2).

Branches and snags were found in a woody layer between two tills and in an adjacent stream about 300 m from the snout of the south tributary glacier of Sphinx Glacier (site a in Figure 3). One of the snags gave an age of 5830 ± 60 14C yr BP (6560–6700 cal. yr BP). A floating ring chronology was built from two of the samples in till and one in the creek (Table 2). The evidence from this site indicates that Sphinx Glacier was about its present size prior to an advance that overrode forest around 5800 14C yr BP.

Wood collected from till near the snout of Sentinel Glacier (Figure 1) in 1970 yielded a radiocarbon age of 6170 ± 150 14C yr BP (6890–7250 cal. yr BP; Lowdon and Blake, 1973). The exact location of this site is unknown, but it is likely to be the same site that we sampled in 2002 (Figure 4a). Our samples range from small trunks to large snags; one of the snags gave an age of 6040 ± 60 14C yr BP (6790–6950 cal. yr BP). The two ages overlap at their 1σ limits, supporting the inference that they are from the same site.

Two samples from the till and two samples in a meltwater stream adjacent to the till exposure were used to construct a floating chronology (Table 2). An in situ stump partially buried in till was collected in 1973 and dated at 5300 ± 70 14C yr BP (5990–6130 cal. yr BP; Lowdon and Blake, 1975). Although we were unable to locate this stump, it is within 1 km of the maximum ‘Little Ice Age’ margin of Sentinel Glacier (Lowdon and Blake, 1975).

The radiocarbon ages from Sentinel Glacier afford a more detailed reconstruction of this event than the ages from Stave, Overlord and Sphinx glaciers. When Sentinel Glacier advanced into forest 6100 14C yr BP, it was about as extensive as today. The dated wood shows little evidence of transport and thus likely had been growing near the sample site prior to the advance. By 5300 14C yr BP, Sentinel Glacier was at least 1 km more extensive than at present and at least half its ‘Little Ice Age’ maximum size. The glacier thus expanded between 6100 and 5300 14C yr BP, although it is not known if glacier growth was slow and continuous or the result of two separate advances.

The Warren Glacier forefield has a similar record (sites b, c, and d in Figure 2). Two in situ stumps (Figure 4c) were found at site d about 100 m from the 2000 glacier margin. They yielded ages of 6370 ± 70 14C yr BP (7250–7330 cal. yr BP) and 6360 ± 80 14C yr BP (7250–7340 cal. yr BP). An exposed and fragmented in situ stump (Figure 4b) at site c about 600 m from the 2000 glacier

| Table 2 | Floating tree-ring chronologies for subalpine fir samples from glacier forefields in Garibaldi Park |
|---|---|---|---|---|
| Glacier | Chronology | 14C age (yr BP) | Length (yr) | Correlation | No. radii/trees |
| Overlord | site ovgl-a | 5890 ± 70 | 138 | 0.562 | 13/4 |
| Helm | sites hegl-b and -c | 4080 ± 40 | 135 | 0.612 | 22/13 |
| Sphinx | site spgl-a | 5830 ± 60 | 184 | 0.404 | 6/3 |
| | site spgl-b | 4280 ± 70 | 115 | 0.698 | 4/2 |
| | site spgl-c | 3560 ± 70 | 197 | 0.427 | 5/3 |
| Sentinel | sites segl-a and -b | 6040 ± 60 | 149 | 0.574 | 8/4 |
| Lava | sites lagl-b, -c, and -d | 5760 ± 60 | 482 | 0.437 | 15/8 |
| | site lagl-f | 5130 ± 40 | 263 | 0.477 | 7/3 |
margin gave an age of 5780 ± 70 14C yr BP (6500–6660 cal. yr BP). A large weathered log partially buried in till at site b yielded an age of 5700 ± 50 14C yr BP (6410–6540 cal. yr BP). We interpret these ages as follows. Warren Glacier was about the same size as today when it advanced into forest at site d about 6350 14C yr BP. By 5800 14C yr BP, the glacier had advanced about 600 m downvalley and was overriding a forest at site c. The dated log at site b, farther downvalley, shows that the glacier continued to advance until at least 5700 14C yr BP. As at Sentinel Glacier, it is not known if Warren Glacier advanced slowly over a period of 650 years or two or more times during this interval.

Garibaldi Neve, an icefield east of Mt Garibaldi, feeds six glaciers, including Lava Glacier (Figure 5). Two in situ stumps on a ridge at the northeast corner of the neve (site a in Figure 5) yielded radiocarbon ages of 6170 ± 60 14C years BP (7000–7160 cal. yr BP) and 6050 ± 50 14C yr BP (6840–6970 cal. yr BP). An in situ stump on a nunatak in the neve was sampled in the 1950s (site Y in Figure 5). It gave ages of 5850 ± 180 14C yr BP (6450–6860 cal. yr BP; Preston et al., 1955) and 5260 ± 200 14C yr BP (5890–6280 cal. yr BP; Stuiver et al., 1960); the latter is assumed to be the more reliable age (Stuiver et al., 1960). The exact location of this sample is unknown, but Figure 5 shows the two possible nunataks in the icefield. Two in situ and three detrital stumps were recovered along the stream draining Lava Glacier about 400 m from the 2003 snout (site b, Figure 5). One of the in situ stumps yielded an age of 5760 ± 60 14C yr BP (6490–6640 cal. yr BP). Two more sites with detrital wood were found in the same area, site c 50 m southeast of site b and site d 110 m northeast of site b. Samples from sites b, c and d were successfully crossdated, providing a floating chronology of almost 500 years (Table 2). Numerous branches, large logs, snags and stumps were found on an alluvial surface (site f, Figure 5), 20–100 m downstream of a gorge eroded in bedrock and till. The surface detrital wood is derived from a wood layer separating two tills within the gorge (arrow near site f in Figure 5). Unfortunately, the site could not be safely accessed. Three detrital stumps at site f were crossdated (Table 2), and a radiocarbon age of 5130 ± 40 14C yr BP (5890–5930 cal. yr BP) was obtained on one of them.

The ages from Garibaldi Neve indicate a thickening of ice between 6100 and 5900/5200 14C yr BP, either slowly or during two separate events. Lava Glacier advanced into mature forests with trees more than 450 years and 250 years old 5800 and 5100 14C yr BP, respectively. It likely had the same extent 5800 14C yr BP as today. By 5100 14C yr BP, when it deposited a till at site f, Lava Glacier was more than half its 'Little Ice Age' size.

**Advance about 4300 14C yr BP (4900 cal. yr BP)**

Evidence for this advance was found only at Sphinx Glacier (site b in Figure 3). Detrital branches and large logs were found in a meltwater stream in the glacier forefield and within a woody layer separating two tills about 500 m from the snout of the southern tributary glacier. The outer 15 rings of one of the logs yielded a radiocarbon age of 4280 ± 70 14C yr BP (4810–4960 cal. BP). A floating chronology, spanning 115 years, was constructed for two samples collected from the till (Table 2). It is unknown if the lower till at site b correlates to the lower till at site a (Figure 3, see ‘Advances between 6400 and 5100 14C yr BP’), thus indicating a single advance, or if the upper till at site a is the lower till at site b, indicating two separate advances. However, evidence at other forefields indicates that glaciers reached much farther downvalley at the end of the previous advance period. It thus is more likely that the tills record two advances and that Sphinx Glacier receded after the 6400–5100 BP advance period to an unknown position...
upvalley of site b for at least 115 years. This issue aside, an advance occurred about 4300 ¹⁴C yr BP, reaching at least site b.

**Advances between 4100 and 2900 ¹⁴C yr BP (4600–3000 cal. yr BP)**

Evidence for one or more advances during this period was found in five glacier forefields in Garibaldi Park. The evidence shows that glaciers became more extensive over time during this period.

Thirteen branches and stumps were found in till near the terminus of Helm Glacier (Figure 6a) in 2003. They appear to be associated with a weathering horizon in the till. A radiocarbon age of 4080 ± 40 ¹⁴C yr BP (4520–4620 cal. yr BP) was obtained on the outermost 12 rings of the sample shown in Figure 6a, and a floating chronology was constructed from all of the samples (Table 2). The evidence suggests that Helm Glacier was less extensive than today for at least 135 years around 4100 ¹⁴C yr BP. Shortly afterwards, it advanced to a more extensive position than at present.

Small wood fragments about 20 m above the present surface of Spearhead Glacier date to 3900 ± 80 ¹⁴C yr BP (4210–4310 cal. yr BP) and 3900 ± 60 ¹⁴C yr BP (4280–4420 cal. yr BP; Osborn et al., 2007). They suggest that Spearhead Glacier was thicker and thus more extensive 3900 ¹⁴C yr BP than today.

Additional evidence for this event was found along the creek draining the southern tributary of Sphinx Glacier (Figure 1) about 800 m from the 2002 snout (site c in Figure 3). A layer of branches and snags occurs within till, and one of the snags gave an age of 3560 ± 70 ¹⁴C yr BP (3820–3930 cal. yr BP). A floating chronology was built from three samples (Table 2). The evidence indicates that the glacier was at least 800 m more extensive 3600 ¹⁴C yr BP than at present.

A large log in the west lateral moraine of Lava Glacier (Figure 6b) yielded a radiocarbon age of 3190 ± 40 ¹⁴C yr BP (3380–3450 cal. yr BP). The log is part of a wood layer that can be traced over a distance of 110 m across several gullies. The till overlying the
wood layer was deposited by Lava Glacier shortly after 3200 $^{14}$C yr BP, when it was about as extensive as at the 'Little Ice Age' maximum.

Decker Glacier also was near its 'Little Ice Age' limit at this time. In situ snags and stumps on a bedrock cliff 40–75 m above the present glacier surface yielded radiocarbon ages of 3200 ± 70 $^{14}$C yr BP (3350–3480 cal. yr BP), 2960 ± 40 $^{14}$C yr BP (3070–3210 cal. yr BP) and 2920 ± 50 $^{14}$C yr BP (2990–3160 cal. yr BP; Osborn et al., 2007). A detrital log below the bedrock cliff gave an age of 2960 ± 50 $^{14}$C yr BP (3060–3220 cal. yr BP). Decker Glacier thickened between 3200 and 2900 $^{14}$C yr BP to near its 'Little Ice Age' maximum extent.

Advances between 1600 and 1100 $^{14}$C yr BP (1500–1000 cal. yr BP)

Evidence for one or more glacier advances in the first millennium AD was found in the forefields of two glaciers in Garibaldi Park. A detrital snag with relatively fine roots, located below a bedrock knob at Sphinx Glacier (site d in Figure 3), yielded an age of 1570 ± 40 $^{14}$C yr BP (1450–1520 cal. yr BP). The roots indicate short transport, and it is likely that the stump was rooted on the bedrock knob. The site is only 600 m from the 2002 ice margin, but the glacier would have to thicken considerably to cover it; thus Sphinx Glacier was much more extensive 1600 $^{14}$C yr BP than at present. Supporting evidence for the same advance or a younger one comes from the forefield of West Stave Glacier. A small log embedded in the outermost lateral moraine close to its crest yielded an age of 1080 ± 60 $^{14}$C yr BP (930–1010 cal. yr BP).

Discussion

Chronology

Glaciers in Garibaldi Park were less extensive than at present throughout the early Holocene. Radiocarbon ages from Wedgemount, Helm and Warren glaciers may record minor advances between 8900 and 8000 $^{14}$C yr BP (Figure 7). However, prior to the 8.2 ka event (Menounos et al., 2004), glaciers must have been less extensive than today, because detrital wood recovered near the margins of Sphinx and Sentinel glaciers dates to 7700–7300 $^{14}$C yr BP.

Warren, Stave, Sentinel, Sphinx, Overlord and Lava glaciers advanced between 6400 and 5100 $^{14}$C yr BP. The glaciers advanced over forests up to 800 m downvalley from present snouts between 6400 and 5800 $^{14}$C yr BP. Sentinel and Lava glaciers were no more than 1–1.5 km from their maximum Holocene limits between 5300 and 5100 $^{14}$C yr BP. It is possible that this event was a single continuous advance that happened over 1300 years, but more likely it was a period like the 'Little Ice Age' with several advances.

Evidence for an advance around 4300 $^{14}$C yr BP was found only at Sphinx Glacier. There, ice advanced at least 500 m farther downvalley than at present (Figure 7). Taken alone, the evidence...
at Sphinx Glacier could be interpreted to indicate slow growth of glaciers between 6000 and 4300 14C yr BP. Combined with evidence from other forefields, however, it is more likely that glaciers receded between 5300 and 4300 14C yr BP to positions similar to the present before readvancing (Figure 7).

Some glaciers achieved present-day extents prior to 4100 14C yr BP, the time that Helm Glacier advanced into forest and deposited till at the site of its present snout. Spearhead Glacier thickened, and Sphinx Glacier advanced up to 800 m, between 3900 and 3600 14C yr BP. Lava and Decker glaciers thickened and advanced into mature forests between 3200 and 2900 14C yr BP, reaching to within 500 m of their Holocene maximum positions at this time. It is not known whether this was a single advance with slow growth over 1200 years or was more complex with several advances.

Sphinx Glacier retreated to its present margins after this advance period, before readvancing into mature forest around 1600 14C yr BP. Stave Glacier was near its Holocene maximum by about 1100 14C yr BP. This advance period was also followed by recession, before the start of the ‘Little Ice Age’ about AD 1000 (Koch et al., 2007).

Regional comparisons
Evidence of glacier activity in the early Holocene in western Canada is sparse, but available data indicate that glaciers were smaller than today at that time (Ryder and Thomson, 1986; Luckman, 1988). Advances during the early Holocene were likely minor and short-lived. Menounos et al. (2004) summarized evidence for an advance in Garibaldi Park at the time of the 8.2 ka cooling event, and a glacier forefield in the Rocky Mountains (Luckman, 1988) also has evidence for this event. Dated samples in Garibaldi Park are near present-day glacier margins, indicating that ice extent was less than today prior to the advance and that the advance was minor.

Glacier advances between 6000 and 5000 14C yr BP in western Canada have been termed the ‘Garibaldi phase’ (Ryder and Thomson, 1986). Evidence for this event has previously been limited to a few sites in the Coast Mountains (Ryder and Thomson, 1986; Laxton et al., 2003; Smith, 2003). Detrital wood in the Canadian Rocky Mountains dating to this period has been interpreted to record treelines higher than today (Luckman et al., 1993), but it may also indicate glacier advance at this time. The Garibaldi phase evidently was a lengthy period during which glaciers achieved fairly extensive positions. It is likely a much more complex event than evidence currently suggests.

Glacier advances between 3300 and 1900 14C yr BP are termed the ‘Tiedemann Advance’ in the Coast Mountains (Ryder and Thomson, 1986). The same event in the Rocky Mountains, although there dated to between 3300 and 2500 14C yr BP, is termed the ‘Peyto Advance’ (Luckman et al., 1993). Evidence for advances at this time is widespread in western Canada (Denton and Stuiver, 1966; Rampton, 1970; Denton and Karlén, 1977; Osborn, 1986; Osborn and Karlstrom, 1989; Luckman et al., 1993; Luckman, 1995, 2006; Jackson and Smith, 2005; Lewis and Smith, 2005; Smith et al., 2005). In most areas, glaciers achieved extents only slightly smaller than during the ‘Little Ice Age’. The Tiedemann/Peyto phase was probably as complex as the ‘Little Ice Age’ and included multiple advances (Luckman, 1995; Reyes and Clague, 2004; Haspel et al., 2005).

Evidence for an advance in the first millennium AD is widespread in western North America (Reyes et al., 2006). Glaciers probably achieved extents at this time that were comparable with those of the preceding and following advance periods.

Climate forcing
Some researchers have noted a relation between Holocene glacier fluctuations and changes in solar activity (Denton and Karlén, 1973; Karlén and Kuylenstierna, 1996). Sunspot numbers and glacier fluctuations in Alaska and western Canada correspond on a decadal timescale over the past millennium (Lawrence, 1950; Wiles et al., 2004; Luckman and Wilson, 2005; Koch et al., 2007). Solanki et al. (2004) inferred sunspot numbers over the past 11 000 years from differences in the production of atmospheric 14C recorded in trees. Comparison of this record with the record of Holocene glacier fluctuations in Garibaldi Park suggests that the major periods of glacier advance correspond with times of low sunspot numbers (Figure 7). This correspondence suggests that changes in solar activity may have affected glacier behaviour in Garibaldi Park and likely elsewhere during the Holocene. The period between 3000 and 4500 cal. yr BP, however, shows little correspondence between glacier activity and solar activity and requires other explanations.

Conclusions
Holocene glacier fluctuations in Garibaldi Provincial Park were determined through geomorphic mapping and radiocarbon dating of detrital and in situ fossil wood in glacier forefields. Glaciers in the park were smaller than at present in the early Holocene. Five major periods of pre-‘Little Ice Age’ glacier advance date to 7700–7300, 6400–5100, 4300, 4100–2900 and 1600–1100 14C yr BP. These periods are broadly synchronous with advances documented elsewhere in western Canada. The evidence from Garibaldi Park suggests that Holocene climate was much more varied than previously thought. Glaciers approached their Holocene maximum positions on three occasions prior to the ‘Little Ice Age’. Glaciers in Garibaldi Park, notably Sphinx Glacier, afford the most complete record of Holocene glacier activity in western Canada. The glacial record is in good agreement with the record of reconstructed sunspot numbers during the Holocene, suggesting that glacier fluctuations in Garibaldi Park may have been forced in part by changes in solar activity.

Acknowledgements
We thank Chris Platz and the other rangers of Garibaldi Park for their support, and Sami Solanki for providing data on sunspot numbers. Will Keats-Osborn, Janet Guglich, Channon Ryane, Vanessa Vallis, Clay Carlson, Scott Carlson and Matt Macleod provided assistance in the field. The Natural Sciences and Engineering Research Council of Canada and Geological Society of America provided funding for the research. Early drafts of the manuscript benefited from reviews by B.H. Luckman, K. Nicolussi, C. Schlüchter and D.J. Smith.

References


Luckman, B.H. and Wilson, R.J.S. 2005: Summer temperatures in the Canadian Rockies during the last millennium; a revised record. Climate Dynamics 24, 131–44.


Preston, R.S., Person, E. and Deevey, E.S. 1955: Yale natural radio carbon measurements II. Science 122, 954–60.


