Midge-inferred Holocene summer temperatures in Southeastern British Columbia, Canada

Marianne Chase\textsuperscript{a}, Christina Bleskie\textsuperscript{b}, Ian R. Walker\textsuperscript{b,⁎}, Daniel G. Gavin\textsuperscript{c}, Feng Sheng Hu\textsuperscript{d}

\textsuperscript{a} Department of Biological Sciences, 2500 University Drive N.W., University of Calgary, Calgary, Alberta, Canada T2N 1N4
\textsuperscript{b} Biology, and Earth & Environmental Sciences, University of British Columbia Okanagan, 3333 University Way, Kelowna, British Columbia, Canada V1V 1V7
\textsuperscript{c} Department of Geography, University of Oregon, Eugene, OR 97403-1251, USA
\textsuperscript{d} Department of Plant Biology, University of Illinois, Urbana, IL 61801, USA

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Abstract

Using fossil midge stratigraphies, we inferred Holocene summer temperatures at three subalpine lakes in eastern British Columbia. The late-glacial sediment indicated cool conditions, with an abundance of \textit{Microspectra atrofasciata/radialis} type fossils at Thunder Lake and Redmountain Lake, and \textit{Sergentia} at Windy Lake. \textit{Sergentia} and \textit{Tanytarsus lugens/Corynocera oliveri} type were dominant in the early Holocene, together with \textit{Chironomus} at Redmountain Lake. At Thunder and Windy lakes, the early Holocene was dominated by warm-adapted taxa such as \textit{Microtendipes}. Quantitative midge-temperature inference models reconstruct a 4 to 8 °C rise in mean July air temperature for Windy and Thunder lakes at the Pleistocene/Holocene transition. Early-Holocene temperatures averaged 3 to 4 °C warmer than those extant today. In contrast, no long-term temperature trend was evident at Redmountain Lake. This site may not reflect actual trends in air temperature due to runoff from a persistent snow pack in the watershed. Comparison of midge and pollen data suggests an inverse relationship between summer temperature and precipitation through the middle to late Holocene.

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1. Introduction

Identifiable remains of Chironomidae and other midges are abundant in lake sediments and used widely for quantitative palaeoclimate reconstruction (e.g., Walker, 1995; Porinchu et al., 2003; Antonsson et al., 2006; Briner et al., 2006). Although the number of fossil midge records is still small relative to the number of fossil-pollen studies, the network of sites is growing rapidly. Midge-based palaeoclimate studies have been conducted throughout much of the world, including locations in Europe (e.g., Brooks, 2006), New Zealand (e.g., Woodward and Shulmeister, 2007), Africa, South America (e.g., Verschuren and Eggermont, 2006), and North America (e.g., Walker and Cwynar, 2006). As the density of study sites and geographic coverage

⁎ Corresponding author. Fax: +1 250 807 8004.
E-mail address: ian.walker@ubc.ca (I.R. Walker).

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increases, midge-based palaeoclimatology will soon allow spatial patterns in postglacial climatic change to be examined.

In 1987, the first postglacial record of fossil midges in British Columbia (BC) was published by Walker and Mathewes (1987). Three additional records were soon added in southern coastal BC (Walker and Mathewes, 1988, 1989). Subsequent midge research established quantitative reconstructions of both temperature and salinity, farther to the east, in the southern interior region (Heinrichs et al., 1997; Smith et al., 1998; Heinrichs et al., 1999; Heinrichs et al., 2001; Palmer et al., 2002; Rosenberg et al., 2004). Palaeosalinity records from low-elevation interior sites were regarded as indicators

Fig. 1. a. Location of our study region (rectangle) in southern British Columbia, Canada. b. Locations of Redmountain Lake, Thunder Lake, and Windy Lake in our study region. Locations of other midge palaeotemperature sites in this region are also indicated: 1. Hippa Lake (Walker and Mathewes, 1988), 2. Misty Lake (Walker and Mathewes, 1989), 3. Marion and Mike Lakes (Walker and Mathewes, 1987, 1989), 4. Frozen Lake (Rosenberg et al., 2004), 5. Cabin Lake and 3M Pond (Smith et al., 1998; Palmer et al., 2002), 6. Crater Lake and Lake of the Woods (Palmer et al., 2002), 7. Eagle Lake (Rosenberg et al., 2004). c–e. Shaded relief maps of the study lakes showing major streams and ice fields.
of hydrological balance (precipitation–evaporation) (Heinrichs and Walker, 2006). Sites at alpine tree-line, where a cool and wet climate results in little evaporative enrichment of lake water, served as sensitive paleothermometers (Walker and Cwynar, 2006).

Midge reproduction depends upon summer air temperature, and as such, past temperature may be well reflected in their relative species abundances preserved within the fossil record (Larocque and Hall, 2003). However, the midge life cycle is also influenced by other aspects of their environment such as pH (e.g., Velle et al., 2005), salinity (Walker et al., 1991) and trophic status (e.g., Broderson and Anderson, 2002). For example, Rosenberg et al. (2004) found that one site produced markedly different midge assemblages relative to surrounding sites, possibly due to changing water depths through the Holocene. Other site-specific factors that might decouple the midge assemblage from air temperature are persistent snow-banks or springs that maintain a low water temperature through the summer (Brooks and Birks, 2000a), or high lakewater salinities derived from high evaporative enrichment. Therefore, it is important to obtain several midge reconstructions within a region to improve the strength of the temperature signal (e.g., Velle et al., 2005). As the midge reconstructions are compared to other proxies, the strength of the signal is further enhanced.

In this paper we outline midge records and derive palaeoclimatic inferences for three new sites from the Columbia Mountains in eastern British Columbia, Canada. These sites expand the British Columbia network farther to the north and east. We also compare the temperature reconstructions with a moisture reconstruction inferred from a major late-Holocene vegetation change.

2. Study sites

Windy Lake, Thunder Lake and Redmountain Lake (informal names; Fig. 1) are small subalpine lakes located within the Engelmann Spruce Subalpine Fir (ESSF) biogeoclimatic zone in the ‘interior wet belt’ of eastern British Columbia. The ESSF is characterized by cool, moist, snowy conditions, and a mean annual

<table>
<thead>
<tr>
<th>Table 1</th>
<th>AMS radiocarbon dates and volcanic tephras from sediment cores from Redmountain Lake, Thunder Lake, and Windy Lake, British Columbia</th>
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<tr>
<td><strong>Depth</strong></td>
<td><strong>Laboratory number or tephra</strong></td>
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<tr>
<td><strong>Windy Lake</strong></td>
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<tr>
<td>42–42.5</td>
<td>St. Helens Wn</td>
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<td>115</td>
<td>114,132</td>
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<td>173</td>
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<td>223</td>
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<td>Mazama ash</td>
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<td>101,682</td>
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<td>475</td>
<td>101,683</td>
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<td>63</td>
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<td>96</td>
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<td>409</td>
<td>101,695</td>
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<tr>
<td>520</td>
<td>114,127</td>
</tr>
</tbody>
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<sup>a</sup> Laboratory numbers assigned by the Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory. Tephra names in italics.

<sup>b</sup> Minimum and maximum of 2σ age ranges only. Calibration follows Reimer et al. (2004).

<sup>c</sup> From Yamaguchi (1983).

<sup>d</sup> From Zdanowicz et al. (1999).

<sup>e</sup> Date rejected.
temperature ranging from −2 to +2 °C (Coupé et al., 1991). Average monthly temperatures may remain below 0 °C for more than five months, while temperatures greater than 10 °C may only occur for up to two months out of the year, if at all. Precipitation is highly variable in this zone, and may vary from as little as 400 mm per year to 2200 mm per year depending on the area. Due to cool conditions, more than half of the annual precipitation is received as snowfall (Coupé et al., 1991). At our study sites, annual precipitation ranges from 1200–1500 mm (Daly et al., 1994). The low-elevation forest below each study site is dominated by western hemlock (Tsuga heterophylla) and subalpine fir (Abies lasiocarpa). On the east shore, forests are interrupted by a fen and avalanche tracks.

Thunder Lake (52°13′42″N, 119°20′54″W; 1539 m a.s.l.), in the Cariboo Mountains between Arrow Lake and the Slocan River (Fig. 1c), is a 3.2 ha cirque basin with a maximum depth of 3.9 m. The bedrock of the area is composed of granite, monzonite, and granodiorite (Massey et al., 2005). Windy Lake is surrounded by continuous forest of Engelmann spruce (Picea engelmannii) and subalpine fir. Abies lasiocarpa). On the east shore, forests are interrupted by a fen and avalanche tracks.

Redmountain Lake (53°55′39″N, 121°17′38″W; 1813 m a.s.l.), in the Selkirk Mountains between Arrow Lake and the Fraser River (Fig. 1e), is a 5.9 ha cirque basin with a maximum depth of 3.9 m. The bedrock of the area is composed of calcareous shale and dolomite (Massey et al., 1991). At our study sites, annual precipitation is received as snowfall (Coupé et al., 1991). Average monthly temperatures may remain below 0 °C for more than five months, while temperatures greater than 10 °C may only occur for up to two months out of the year, if at all. Precipitation is highly variable in this zone, and may vary from as little as 400 mm per year to 2200 mm per year depending on the area. Due to cool conditions, more than half of the annual precipitation is received as snowfall (Coupé et al., 1991). Windy Lake (49°48′48″N, 117°52′38″W; 1813 m a.s.l.), in the Selkirk Mountains 13 km north of Blue Mountain Lake, is a 19.7 ha basin with a maximum depth of 2.9 m. The bedrock is composed of granite, monzonite, and granodiorite (Massey et al., 2005). Windy Lake is surrounded by continuous forest of Engelmann spruce (Picea engelmannii) and subalpine fir (Abies lasiocarpa). On the east shore, forests are interrupted by a fen and avalanche tracks.

At Windy Lake and Redmountain Lake, the lack of stratigraphic discontinuities and the strong visual correlation between parallel core drives (not shown) suggest little local perturbation of the sediment. Therefore, we used samples from well-correlated overlapping core drives to derive a continuous, composite record of the areas’ sediment. Ages were assigned to sample depths by interpolating between dates using a cubic spline curve fit. At Thunder Lake, above the Mazama tephra, parallel core drives correlated poorly with each other. Therefore, we obtained samples from a single core. Subsequent radiocarbon dating revealed a major age discontinuity between two core drives at 100 cm, resulting in a gap in the record between 2700 and 4600 cal yr BP. We conservatively assigned sample ages at Thunder Lake using linear interpolation.

### 3.2. Midge analyses

Sediments were processed following the standard procedures outlined in Walker (2001). Sediment volumes were measured by displacement in de-ionized water. Pretreatment procedures involved carbonate removal in 10% HCl and deflocculation in warm 5% KOH. The resulting slurry was washed on a 95 μm Nitex sieve. Sediment retained on the sieve was washed with de-ionized water into a beaker. This residue was later hand(sorted in a Bogorov counting tray using a dissecting microscope at 25–50× magnification, and fine-tipped forceps. In addition to chironomid (non-biting midge), ceratopogonid (biting midge) and simulid (black fly) head capsules, the remains of Acari (mites), and mandibles of Chaoborus (phantom...
midges) and Ephemeroptera (mayflies) were separated from the sediment. The fossil remains were transferred onto coverslips, allowed to air dry, and ultimately mounted onto glass slides using Entellan® mounting medium.

Sampling was focused at Windy Lake because this site had the best sediment chronology and chironomid preservation. At Windy Lake 0.5 to 2.5 ml of sediment was processed from 75 intervals spanning 45 to 575 cm. At Thunder Lake 0.5 to 1.5 ml of sediment was processed from 20 intervals spanning 15 to 350 cm. At Redmountain Lake 0.4 to 5.4 ml of sediment was processed from 31 intervals spanning 1 to 575 cm. We sought to obtain a minimum of 50 midge remains from each level (Heiri and Lotter, 2001; Larocque, 2001; Quinlan and Smol, 2001). Because sufficient sediment was not available for the analyses, this quota was not met at a few levels, most notably in the earliest postglacial sediments.

Identifications were made using BH-2 and BX51 Olympus compound microscopes at magnifications of 100–400×. Chironomids were identified primarily according to illustrations, keys and descriptions contained within Oliver and Roussel (1983), Wiederholm (1983), Schmid (1993), and the WWW Field Guide to Subfossil Midges (Walker, 2000) as well as a photographic reference collection maintained at the University of British Columbia Okanagan.

3.3. Data analysis

Data were collated using TILIA version 2.0.b.4 (Grimm, 1993). TGVIEW 2.0.2 was used to prepare percentage stratigraphic diagrams (Grimm, 2004). The stratigraphies were subdivided into a series of zones via CONISS (Grimm, 1987), following square-root transformation of the data.

Mean July air temperature was estimated for each fossil midge assemblage using a database of 53 modern midge assemblages from lake sites in southern British Columbia that occur over a geographic gradient of summer temperature (Rosenberg et al., 2004). Several rare taxa in the fossil midge assemblages were merged into higher taxonomic groups to harmonize the fossil midge taxonomy with that used by Rosenberg et al. (2004). We used seven inference models for the temperature reconstructions because of strengths and weaknesses associated with each model (Lotter et al., 1999). The modeling methods included 1) Weighted averaging (with both classical (WA_class) and inverse deshrinking (WA_inv), with and without tolerance downweighting (WA(tol)_class and WA(tol)_inv); weighted-averaging partial least squares (WAPLS-2), and partial least squares regression (PLS-1) in CALIBRATE vers. 0.82 (ter Braak and Juggins, 1993; ter Braak et al., 1993; Juggins, 1997). Descriptions of the models may be found in Palmer et al. (2002). For lack of a ‘best’ model, we present all model results, and a robust mean that down-weights outliers (Tukey biweight mean; Mosteller and Tukey, 1977), for each sample.

4. Results

4.1. Windy Lake

4.1.1. Sediment lithology and chronology

The Windy Lake sediment core (590 cm) consisted of sand, silt, and clay (<3% LOI) from the base to
Fig. 3. Percent midge stratigraphy diagram for Windy Lake. Chironomid species are ordered by increasing temperature optima from left to right. Taxa without known optima for our area are placed to the right of the diagram. A few rare taxa have been excluded.
Fig. 4. Chironomid-inferred reconstructions of mean July air temperature at a) Windy, b) Thunder, and c) Redmountain lakes, British Columbia: WAINV (Weighted Averaging, deshrinking by inverse regression), WAINV(tol) (Weighted Averaging with tolerance down-weighting, deshrinking by inverse regression), WACLS (Weighted Averaging, deshrinking by classical regression), WACLS(tol) (Weighted Averaging with tolerance down-weighting, deshrinking by classical regression), WAPLS-2 (Weighted averaging partial least squares with 2 components), PLS-1 (Partial least squares with 1 component), PLS-2 (Partial least squares with 2 components). The fitted line is based on a robust mean of the seven temperature estimates from each sample. The approximate modern mean July temperature at each site is estimated to be ca. 10 °C, and is indicated for each site for reference. The horizontal bars indicate major climatic events, including glacial advances as identified elsewhere in the Columbia and Rocky Mountains (Peyto Advance, Luckman et al., 1993; Little Ice Age, Luckman, 2000).
476 cm. At 476 cm (11,400 cal yr BP), the sediment transitioned abruptly to gyttja (Fig. 2). With the exception of a thick Mazama tephra at 373–287 cm, the sediment consisted of uniform dark brown gyttja (30–45% LOI) from 476 cm to the surface. The radiocarbon dates indicate a relatively constant sediment accumulation rate through the Holocene.

4.1.2. Midge stratigraphy

The subtribe Tanytarsina and Procladius dominate throughout most of the core (Fig. 3). In addition to large numbers of lacustrine species, small numbers of rheophilous midges (e.g., Rheocricotopus) are present throughout, and are likely derived from small, possibly intermittent streams or seeps entering the lake. CONISS and visual inspection suggested four zones (Fig. 3).

4.1.2.1. Zone WIN-1 (525–455 cm; 13,000–10,700 cal BP). This zone is characterized by the high abundance of subtribe Tanytarsina, and by the occurrence of two cold-stenothermic taxa, Stictochironomus and Tanytarsus lugens/Corynocera oliveri type. Warm water taxa such as Polypedilum and Tribe Pentaneurini occur sporadically within the zone, but only at trace abundance. The warm-adapted Dicrotendipes is an exception, and accounts for nearly 20% of the midges at the beginning of this zone. The abundance of cold stenotherms and dearth of warm-water taxa is typical for late-glacial assemblages, reflecting the cold climate that prevailed during deglaciation (Walker and Mathewes, 1987, 1989; Thompson et al., 1993; Smith et al., 1998; Palmer et al., 2002; Rosenberg et al., 2004).

4.1.2.2. Zone WIN-2 (455–403.5 cm; 10,700–8800 cal BP). Overall this zone is characterized by an abundance of warm-adapted taxa, and a decrease in cold-stenotherms. Stictochironomus and Tanytarsus lugens/Corynocera oliveri type are rare. Warm-adapted midges such as Microtendipes, Endochironomus, Glyptotendipes, Stempellinella/Zavrelia, and Chaoborus are more abundant in zone WIN-2 than elsewhere in the core. This zone is also marked by a lower abundance of subtribe Tanytarsina than observed for the other three zones. The prevalence of warm-adapted taxa is indicative of significantly higher temperatures during the early Holocene than today.

4.1.2.3. Zone WIN-3 (403.5–267.5 cm; 8800–6900 cal BP). Dominant taxa include Tanytarsina, Procladius and Chironomus. Warm water midges, such as Microtendipes, Endochironomus, Glyptotendipes, Stempellinella/Zavrelia, and Chaoborus decrease or disappear in zone WIN-3, suggesting a decrease in summer temperatures during the middle Holocene.

4.1.2.4. Zone WIN-4 (267.5–45 cm; 6900–500 cal BP). Subtribe Tanytarsina, Procladius, Cricotopus/Orthocladius and Psectrocladius dominate this zone. Warm-water midges (e.g., Microtendipes, Polypedilum) constitute only a trace of the fauna. In contrast, several cold-adapted and eurythermic midges (e.g., Psectrocladius, Micropsectra, Cricotopus/Orthocladius, Protaanypus, Diamesa, Oliveridia/Hydrobaenus, Pagastia, Pseudodiamesa, and Tanytarsus lugens/Corynocera oliveri type) are more abundant. This suggests a further decrease in summer temperatures during the late Holocene.

4.1.3. Temperature reconstruction

During the late-glacial period, summer temperatures at Windy Lake ranged between 6.5 and 12 °C (Fig. 4a). The coldest temperatures are inferred ca. 12,500 cal yr BP in the midst of the Younger Dryas chronzone. The transition from the late glacial to early Holocene was marked by a rapid increase in inferred summer temperatures, rising to 13.5 to 14.5 °C ca. 11,500 to 10,500 cal yr BP. Early-Holocene summer temperatures remained 3 to 4 °C warmer than today from 10,500 to 9000 cal yr BP. Early-Holocene temperatures reached a low of 10.4° ca. 8250 cal yr BP. Midge-inferred temperatures then rose by a couple of degrees, until ca. 6000 cal yr BP, when air temperatures cooled to nearly 9 °C, and remained around an average of 9.5 °C throughout the remainder of the mid to late Holocene (Fig. 4a).

4.2. Thunder Lake

4.2.1. Sediment lithology and chronology

The Thunder Lake sediment core consisted of sand, silt, and clay (ca. 5% LOI) from the core base (345 cm) to 318 cm (Fig. 2). With the exception of a 32-cm Mazama tephra layer, the sediment above 295 cm consisted of uniform dark brown gyttja (30–40% LOI). The start of the transition to organic sediments at 318 cm dated to ca. 11,000 cal yr BP.

4.2.2. Midge stratigraphy

The Thunder Lake midge stratigraphy was divided into three major zones based on cluster analysis and visual inspection (Fig. 5). The subtribe Tanytarsina dominated the chironomid community throughout the core; however, this is a broad taxonomic group and as such does not provide much information regarding temperature (Smith,
Fig. 5. Percent midge stratigraphy diagram for Thunder Lake. Chironomid species are ordered by increasing temperature optima from left to right. Taxa without known optima for our area are placed to the right of the diagram. A few rare taxa have been excluded.
Redmountain Lake, British Columbia, Canada
Midge Percentage Diagram

Fig. 6. Percent midge stratigraphy diagram for Redmountain Lake. Chironomid species are ordered by increasing temperature optima from left to right. Taxa without known optima for our area are placed to the right of the diagram. A few rare taxa have been excluded.
Chironomus, a eurythermic genus was also abundant throughout much of the core (Fig. 5).

4.2.2.1. Zone THU-1 (350–300 cm; 12,700–10,300 cal BP). This zone is characterized by the very high abundance of subtribe Tanytarsina head capsules. The zone begins with Microspectra atrofasciata/radialis type, a cold stenothermic taxon, accounting for nearly 15% of the midges found. Subsequently, M. atrofasciata/radialis type decreases in abundance. Near the end of the zone there is a small peak in the warm indicator Pagastiella.

4.2.2.2. Zone THU-2 (300–97.5 cm; 10,300–3000 cal BP). This zone has a much more diverse midge assemblage. It is distinguished especially by the greatly decreased abundance of Tanytarsina, and by high relative abundances of Cladotanytarsus mancus and Chironomus. Although two Chironomus species are reported from the high arctic (Danks, 1981), most Chironomus are associated with warm water habitats. Psectrocladius are eurythermic and much more abundant in zone THU-2 than previously. A broad peak in Microtendipes abundance, and the peak abundance of Chaoborus suggest that summer temperatures may have been highest early in this zone. Several other midge taxa commonly associated with warm, low-elevation lakes (e.g., Polypedilum, Tribe Pentaneurini, Cladopelma and Glyptotendipes) also occur as trace components of this zone’s fauna.

4.2.2.3. Zone THU-3 (97.5–15 cm; 3000–250 cal BP). This zone is distinguished by a return to Tanytarsina dominance, and a reduction of warm-water taxa including Chironomus. Although Psectrocladius remains abundant in zone THU-3, the assemblage is otherwise very similar to that in THU-1, suggesting a return to climatic conditions similar to those extant during the late glacial or earliest Holocene.

4.2.3. Temperature reconstruction

Midge-inferred temperatures of the early Holocene fluctuate about an average of 11.7° at Thunder Lake (Fig. 4b). The temperature trend is similar to that of Windy Lake, with the late Holocene being cooler than the early Holocene (by about 1.5°).

4.3. Redmountain Lake

4.3.1. Sediment lithology and chronology

Below 550 cm sediments were highly inorganic (LOI<2%) and chironomid remains were absent. Continuous light gray silts and clays with indistinct banding are evident between 550 and 300 cm, but these are also inorganic (<10% LOI; Fig. 2). Above 300 cm the sediment core consisted of distinctly banded brown–gray silts and clays (ca. 4% LOI). Radiocarbon dates indicate very slow sediment accumulation rates before ca. 5000 cal yr BP (400 cm) and a fairly constant sediment accumulation rate thereafter (Fig. 2). No volcanic tephras were evident in this core.

4.3.2. Midge stratigraphy

A large proportion of the midge remains were unidentifiable owing to poor preservation in the Redmountain Lake core, and had to be excluded from the statistical analysis and interpretation. The subtribe Tanytarsina were the dominant midges throughout the Redmountain Lake core, Chironomus and Sergentia were the next most prominent, followed by Tanytarsus lugens/Corynocera oliveri type, and Procladius. Rheocricotopus, Parametriocnemus type, Limnophyes and Doithrix/Pseudorthocladius type are rhipheophilous taxa derived from small streams entering Redmountain Lake. CONISS identified two zones in the Redmountain Lake stratigraphy (Fig. 6).

4.3.2.1. Zone REDMTN-1 (580–540 cm; 10,700–10,500 cal BP). This zone is distinguished especially by the great abundance of Microspectra atrofasciata/radialis type.

4.3.2.2. Zone REDMTN-2 (540–0 cm; 10,500 cal BP–present). The subtribe Tanytarsina remains dominant through this zone, but Microspectra now constitutes only a trace component of the fauna. The subzones are indistinct, but reflect an increased abundance of Chironomus remains in the upper half of the Redmountain Lake core.

4.3.3. Temperature reconstruction

In contrast to Windy Lake and Thunder Lake, Redmountain Lake temperature reconstructions indicate very little millennial-scale trend (Fig. 4c). In particular, the four early-Holocene samples from Redmountain Lake do not show higher summer temperatures than the samples from the mid to late Holocene. Throughout the Holocene temperatures range from 8.0° to 11.2°, with an average of 9.6°.

5. Discussion

Redmountain Lake exhibits very little trend in temperature. However, the Holocene temperature reconstruction for Thunder Lake parallels that of Windy, with a
warm early Holocene and cool late Holocene. The validity of the reconstructions is supported by a general trend, most striking in the early Holocene, of decreasing temperatures with increasing latitude, from Windy Lake to Redmountain Lake (Fig. 4).

Our discussion of palaeoclimatic records focuses on our southernmost site, Windy Lake, since this site provides the longest, best-dated, and highest-resolution record. The Windy Lake record comprises three distinct phases: 1) a cold late-glacial interval prior to 11,000 cal yr BP, 2) an early-Holocene thermal maximum (ca. 10,500 to 6500 cal yr BP), and 3) a comparatively cool late-Holocene interval (ca. 6000 cal yr BP to today).

5.1. Late-glacial climate

Midge-inferred summer temperatures at Windy Lake varied from about 6.5 to 12 °C through the late glacial, averaging about 1 to 2 °C cooler than today. The sample resolution is inadequate to confidently resolve the late-glacial pattern of climatic change; higher resolution sampling would be necessary to fully resolve a Younger Dryas signal, or the signature of any similar late-glacial climatic oscillations. The Younger Dryas’ occurrence has been well-documented in eastern Canada (e.g., Levesque et al., 1997; Whitney et al., 2005), and throughout much of Europe (e.g., Brooks and Birks, 2000b; Ponel et al., 2007). It has also been reported by Mathewes (1993) and Mathewes et al. (1993) in coastal British Columbia, and by Reasoner et al. (1994) from the Canadian Rocky Mountains. Walker and Pellatt (2003) argue, however, that a temperature oscillation is not clearly evident in the records from western Canada, and the observed changes possibly pertain to shifts in prevailing wind directions and precipitation, accompanying the Cordilleran Ice retreat. They argue that the late-glacial changes in southwestern British Columbia may be part of a time-transgressive sequence south of the Cordilleran ice sheet with a cause separate from that of the Younger Dryas event.

5.2. Early-Holocene climate

At Windy Lake inferred summer temperature warmed rapidly at the late-glacial/Holocene transition to 13.5 to 14.5 °C. The range in temperature from the late glacial to the early Holocene exceeds the standard error of estimates from individual models, which are typically about 2 °C (Palmer et al., 2002). This early-Holocene warming is similar in magnitude and timing to those inferred at five sites to the west of our study region on the Thompson Plateau and in the Cascade Mountains of southwestern British Columbia (Smith et al., 1998; Palmer et al., 2002; Rosenberg et al., 2004). On an international scale, the timing of the transition from Younger Dryas to early Holocene corresponds to that recorded in the GISP2 core of Greenland, and cores from France and Norway, although the magnitude of warming in Greenland and France is two or three times that observed in the Windy Lake core (Grootes et al., 1993; Brooks and Birks, 2000c; Ponel et al., 2007).

Early-Holocene summer temperatures remained 3 to 4 °C warmer than today from 10,500 to 9000 cal yr BP. This inference is also supported by palaeobotanical and midge evidence at other sites (Mathewes, 1985; Hebda, 1995; Palmer et al., 2002; Walker and Pellatt, 2003; Rosenberg et al., 2004). Tree-line in BC, for example, was higher than present during the early to mid-Holocene, as especially indicated by radiocarbon dates on stumps preserved above the present-day limit of trees (Clague and Mathewes, 1989).

The lowest early-Holocene temperature inference dates to ca. 8250 cal yr BP (ca. 2 °C cooler than the adjacent periods), and coincides with a brief cold episode recorded in the GISP2 ice core and possibly in palaeoclimate records from other regions of the northern hemisphere (Alley et al., 1997). Pisaric et al. (2003) have suggested that depression of treeline at a small lake in northeastern British Columbia might have been triggered by a cooling ca. 8200 cal yr BP. In contrast, Kurek et al. (2004) found that chironomid records from eastern North America were unable to detect the 8200 cal yr BP event, possibly because this event was relatively short-lived (i.e., centennial-scale; Alley et al., 1997). While interesting, our record does not have sufficient temporal resolution to properly evaluate the correspondence of the Windy Lake early-Holocene minimum with the GISP2 8200 cal yr BP cooling event.

For the interval 8000 to 6500 cal yr BP, inferred summer temperatures remained 1.5 to 2.5 °C warmer than today. Similar temperatures to those of today were established by about 6000 cal yr BP, and temperatures continued to decrease until ca. 4000 cal yr BP (Fig. 4). This general trend of decreasing summer temperature has been widely documented in western North America (e.g., Hebda, 1995; Walker and Pellatt, 2003) and is consistent with decreasing summer insolation through this period (Thompson et al., 1993).

Redmountain Lake temperature reconstructions fail to display a significant trend. Because the Redmountain Lake sediments were very low in organic content and midge concentrations, the record is relatively sparsely sampled. However, additional samples would not likely affect the lack of a millennial-scale trend at this site. This lake occupies a high-elevation cirque where snowfields...
are likely to persist throughout the summer. Meltwater from these snowfields may rapidly replenish the lake as may be indicated by the presence of rheophilous taxa such as Rheocricotopus, Parametriocnemus type, Limnophyes and Doithrix/Pseudorthocladius type (Gandouin and Franquet, 2002). This, and the shade offered by steep mountains ridges to the south and west likely maintain cooler conditions at Redmountain Lake than would otherwise be expected at this elevation (Livingstone et al., 1999; Brooks and Birks, 2000a).

The above explanation for the insensitivity of the Redmountain Lake record would be consistent with this site being situated far from an aquatic ecotone. For example, Heegaard et al. (2006) note that distinct aquatic ecotones exist in the Swiss Alps; such ecotones likely also exist in the Cordillera. Sites close to ecotonal boundaries are likely highly sensitive to climatic changes while sites distant from these boundaries may be insensitive (e.g., Weckström and Korhola, 2001; Nyman et al., 2005; Walker, 2006). Unlike their terrestrial counterparts, aquatic ecotones are inconspicuous and their positions can only be recognised after extensive regional surveys of lake biota.

Although the existence of an early-Holocene warm interval is well established in southern British Columbia, few palaeoclimatic studies have been conducted in the northern or central regions of the province; thus, the pattern of Holocene climatic change will require further study in these areas. Recent midge analyses at sites farther north, in the Yukon and Alaska (Barley, 2004; Stepanovic’, 2006), suggest that the early-Holocene thermal maximum, if it existed in eastern Beringia, was much weaker than is evident in southern BC.

5.3. Late-Holocene climate

All three sites show generally cool temperatures and little millennial-scale trend during the late Holocene. The transition to cooler temperatures at Windy Lake occurs at approximately 6000 cal yr BP, while that at Thunder appears to occur sometime between 4500 and 3000 cal yr BP, with Redmountain Lake maintaining cool temperatures throughout the Holocene. Other evidence of cooler periods within the late Holocene includes an oxygen isotope record from the Yukon Territory (Anderson et al., 2005) and widespread evidence of nearby glacial advances in the Columbia and Rocky Mountains (Osborn and Karlstrom, 1988; Luckman et al., 1993; Luckman, 2000). In the Yukon Territory, an initial drop in temperature is observed at approximately 4500 yr BP, before warming at 3500 cal yr BP and cooling once more at 1200 cal yr BP (Anderson et al., 2005). In the Columbia and Rocky Mountains, periodic glacial advances are recorded from approximately 3300 cal yr BP (Osborn and Karlstrom, 1988; Luckman et al., 1993) and 800 cal yr BP onward (Luckman, 2000).

The late-Holocene temperature reconstructions presented here agree well with five of the six midge-palaeotemperature records previously published for British Columbia (Palmer et al., 2002; Rosenberg et al., 2004). These sites generally indicate a mid-Holocene cooling trend, with cool temperatures prevailing through the late Holocene. Rosenberg et al.’s (2004) Eagle Lake site is anomalous, indicating a late-Holocene warming.

The late-Holocene temperature reconstructions presented here also agree well with the climatic interpretation of vegetation changes. A major feature of the late-Holocene vegetation in our study area is the establishment of the low-elevation dominant forest species, western hemlock and western red cedar, ca. 3000–4000 yr BP (Rosenberg et al., 2003). The modern distributions of these species are characterized by a main coastal range and a disjunct interior range in the Columbia Mountains near our study sites, the latter of which is commonly referred to as the ‘interior wet belt’. This region contrasts with surrounding areas due to

Fig. 7. Comparison of Cooley Lake western hemlock pollen record (7600 yr BP to present) with the Windy Lake temperature reconstruction.
increased evapotranspiration from more moist summers and a lack of a moisture deficit (Gavin and Hu, 2006). Thus, the pollen record of western hemlock expansion in the late Holocene may reflect increasing effective summer moisture. This interpretation of western hemlock pollen contrasts with that from records a short distance east of the coastal hemlock zone. In these coastal areas, hemlock pollen has been interpreted as a proxy of the strength of onshore winds that transport pollen inland (Cwynar, 1993; Spooner et al., 2003). This mechanism is not applicable at our sites, which are quite removed (200–400 km) from the coastal hemlock populations.

We overlaid the western hemlock pollen record from Cooley Lake (39 km to the SE of Windy Lake; Gavin et al., 2006), with the temperature reconstruction from Windy Lake (Fig. 7). This comparison shows that hemlock increased in the region within 1000 yr of temperatures reaching values typical of the neoglacial cooling at ca. 4600 cal yr BP. Such a time lag is possible considering the long life span of western hemlock, the competitive post-fire conditions which are frequent in the region, and its possible dispersal route. We suggest two ways in which effective moisture increased at ca. 4600 cal yr BP. First, lower summer temperatures would have placed less evaporative demand on trees, reducing drought injury on species susceptible to moisture deficits, such as western hemlock. Second, lower summer temperatures may be associated with increased onshore flow, delivering Pacific moisture to the interior. Such periods would be characterized by a relatively weak Pacific Subtropical High, and would be consistent with decreasing summer insolation through the mid to late Holocene at this latitude (Thompson et al., 1993). Therefore, a late-Holocene weakening of the Pacific Subtropical High could result in both cooler summer temperature and increased precipitation.

6. Conclusion

Midge-inferred palaeoclimatic reconstructions suggest an initial warm period during the early Holocene followed by cooler conditions beginning in the mid or late Holocene at both Thunder and Windy lakes. The palaeoclimatic reconstruction at Windy and Thunder lakes follows the trend observed for five of the six documented lakes within southern British Columbia, but with a summer-temperature minimum at 8250 cal yr BP at Windy Lake. The palaeoclimatic reconstruction for Redmountain Lake lacks evidence of a warmer early Holocene. This site may be affected by local climate conditions such that runoff from local snowpack influences summer water temperatures. Comparison of these summer temperature reconstructions with reconstructed summer moisture inferred from western hemlock pollen suggests an inverse relationship between summer temperature and precipitation through the mid to late Holocene.

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