Quaternary Research 77 (2012) 355–367

Contents lists available at SciVerse ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Temperatures of the past 2000 years inferred from lake sediments, southwest Yukon Territory, Canada

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ARTICLE INFO

Article history:
Received 19 October 2010
Available online 13 February 2012

Keywords:
Chironomids
Ostracodes
Lake sediments
Quantitative paleoclimate reconstructions
Yukon Territory
Late Holocene
Little Ice Age
Medieval Climate Anomaly

ABSTRACT

Lake sediments from four sites in the southwest Yukon Territory, Canada, provided paleotemperature records for the past 2000 yr. An alpine and a forest site from the southeastern portion of the study area, near Kluane Lake, and another alpine-forest pair of lakes from the Donjek River area located to the northwest yielded chironomid records that were used to provide quantitative estimates of mean July air temperature. Prior to AD 800, the southwest Yukon was relatively cool whereas after AD 800 temperatures were more variable, with warmer conditions between ~AD 1100 and 1400, cooler conditions during the Little Ice Age (~AD 1400 to 1850), and warming thereafter. These records compare well with other paleoclimate evidence from the region.

Introduction

Well-documented climate variations over the past 2000 yr include a period of generally cool conditions during the Little Ice Age (~AD 1450 to 1850) and relatively warmer temperatures during the Medieval Climate Anomaly (~AD 950 to ~1250; Mann et al., 2009). Although the nature of the Little Ice Age is quite well known and it is recognized that the climate variations during this time occurred globally, knowledge of medieval warming is less established and there is still debate about its geographic extent (e.g., Jones et al., 2009; Mann et al., 2009). Recently, a group of high-temporal-resolution paleoclimate reconstructions at sites spanning northern North America, Greenland, Iceland, and Fennoscandia were assembled to assess climate variations across the northern latitudes over the past 2000 yr; however, there were no records from the Yukon Territory in that compilation (Kaufman, 2009).

Holocene climate reconstructions based on pollen data, with a temporal resolution of 100 yr, indicate relatively warm conditions between 1800 and 1100 cal yr BP and cooler conditions around 400 cal yr BP in western Canada (Viau et al., 2008). Regional records from the Yukon Territory provide information about changes in temperature and precipitation on both long (13,000 yr; Bunbury and Gajewski, 2009a; Kurek et al., 2009) and short (300 yr; Youngblut and Luckman, 2008) timescales, but currently no studies have targeted the past two millennia. Bunbury and Gajewski (2009a) derived paleotemperature and paleoprecipitation estimates from pollen and chironomid assemblages in a 13,600-yr record from Upper Fly Lake but there were too few samples in the upper sediments to reliably interpret the tendencies during the past 2000 yr. Youngblut and Luckman (2008) used seven tree-ring chronologies to reconstruct maximum June–July temperatures in the region for the last 300 yr. These records indicate cooler temperatures from AD 1690 to 1720 and in the early and late 1800s, and warmer temperatures between AD 1720 and 1800, centered around AD 1850, and after 1900.

Oxygen isotope records from an ice core on Mt. Logan (Fisher et al., 2004), and from lake sediments (Anderson et al., 2005; Anderson et al., 2007; Anderson et al., 2011) were used to infer variations in the moisture regime in the southern Yukon Territory during the Holocene. The Jellybean Lake isotope record is thought to reflect variability in the intensity and position of the Aleutian Low Pressure Centre over the past 7000 yr (Anderson et al., 2005). Situated over the Gulf of Alaska, this semi-permanent low pressure cell affects moisture delivery to the St. Elias Mountains and the interior southern Yukon Territory (Wahl et al., 1987). During the mid- to late Holocene, a weak and/or westward positioned Aleutian Low corresponded with wetter conditions in the interior, whereas drier conditions were associated with an eastwardly located, and/or more intense pressure center (Anderson et al., 2005). Changes in the hydrologic balance in the southern Yukon Territory inferred from oxygen isotope records in Marcella and Seven Mile Lake sediments are also interpreted as a response to changes in the Aleutian Low over the past 4500 yr (Anderson et al., 2007) and 1000 yr (Anderson et al., 2011), respectively, and indicate that effective moisture was higher from

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doi:10.1016/j.yqres.2012.01.002

3000 cal yr BP until AD 1600, followed by more arid conditions. These records have established that changes in "effective moisture" are an important manifestation of climate variability in the region.

In this paper, we present a paleoenvironmental interpretation of the past 2000 yr based on the analysis of chironomids, ostracodes and sediment data from four sites in the southwest Yukon Territory. Since quantitative paleoclimate records of the past two millennia are lacking from this region, we derive chironomid-based estimates of the mean July air temperature using a modern calibration set including modern samples from northwest North America.

Study sites

Sediment cores were collected from four lakes in the interior southwest Yukon Territory (Fig. 1). Two of the lakes are located in the southeast and two in the northwest, with boreal and alpine locations in each region. The climate in the region is semi-arid due to the orographic effect of the St. Elias Mountains situated to the southwest of the study area. Mean January and July temperatures at Otter Falls Station (61°1.8′N, 137°3.0′W, 830 m a.s.l.) are −16.4°C and 13.1°C, respectively, and total annual precipitation is 297 mm (Environment Canada, 2000). Farther north at Burwash Landing (61°13.2′N, 139°18.0′W, 807 m a.s.l.), mean January temperatures are cooler (−22°C), whereas mean July temperatures and total annual precipitation values are comparable (12.6°C and 280 mm). Sites to the southeast are located in the Upper Yukon–Stikine Basin climatic region, where the orographic effects of the St. Elias Mountains increase aridity, particularly in the Kluane Lake area (Wahl et al., 1987). In addition, the elevations are higher, permafrost is less continuous (National Atlas Information Service, 1995) and the boreal forest is dominated by white spruce. In comparison, sites to the northwest are situated in the Central Yukon Basin where elevations are lower, winter temperatures are colder, black spruce is more abundant, permafrost is more continuous, and the effects of the Aleutian Low over the Gulf of Alaska are less pronounced (Wahl et al., 1987).

Upper Fly Lake (unofficial name) is located at alpine treeline (61.04°N, 138.09°W, 1326 m a.s.l., 10.5 ha surface area; Fig. 1). The lake is underlain by gneiss bedrock (Wheeler et al., 1997) with surficial deposits of glaciolacustrine silts and clays (Fulton, 1995). Alpine tundra plants dominate in the catchment and include dwarf birch (*Betula* spp.), shrub willow (*Salix* spp.), along with typical alpine herbaceous plants. Several individuals of white spruce (*Picea glauca*) are growing on the slopes alongside the lake. There is no surface inflow and outflow is via a stream into Fly Lake.

Jenny Lake (61.04°N, 138.36°W, 817 m a.s.l., 19.9 ha) is underlain by gneiss bedrock overlain by thick, continuous glacial till (Fulton, 1995; Wheeler et al., 1997; Fig. 1). Dominant trees in the catchment are white spruce (*Picea glauca*), balsam poplar (*Populus balsamifera*), and trembling aspen (*Populus tremuloides*), and the boreal forest surrounding the lake is interspersed by small grasslands bordered by shrubs such as *Shepherdia canadensis*, *Salix* spp. and groves of *Populus* spp. Jenny Lake has no visible surface inlets or outlets.

Donjek Kettle (unofficial name; 61.69°N, 139.76°W, 732 m a.s.l., 0.6 ha) is adjacent to the Alaska Highway and is situated on thick, continuous glacial till underlain by intrusive rocks, particularly granodiorite and quartz diorite (Fulton, 1995; Wheeler et al., 1997; Fig. 1). Boreal forest surrounds the lake as at Jenny Lake, although alder (*Alnus* spp.) is present here. There are no surface inflows or outflows.

Lake WP02 (unofficial name; 61.48°N, 139.97°W, 1463 m a.s.l., 0.65 ha) is underlain by volcanic rock, which is overlain by a thin, discontinuous till veneer (Fulton, 1995; Wheeler et al., 1997; Fig. 1). Alpine tundra vegetation surrounds the lake and no surface streams were observed flowing into or out of the lake.

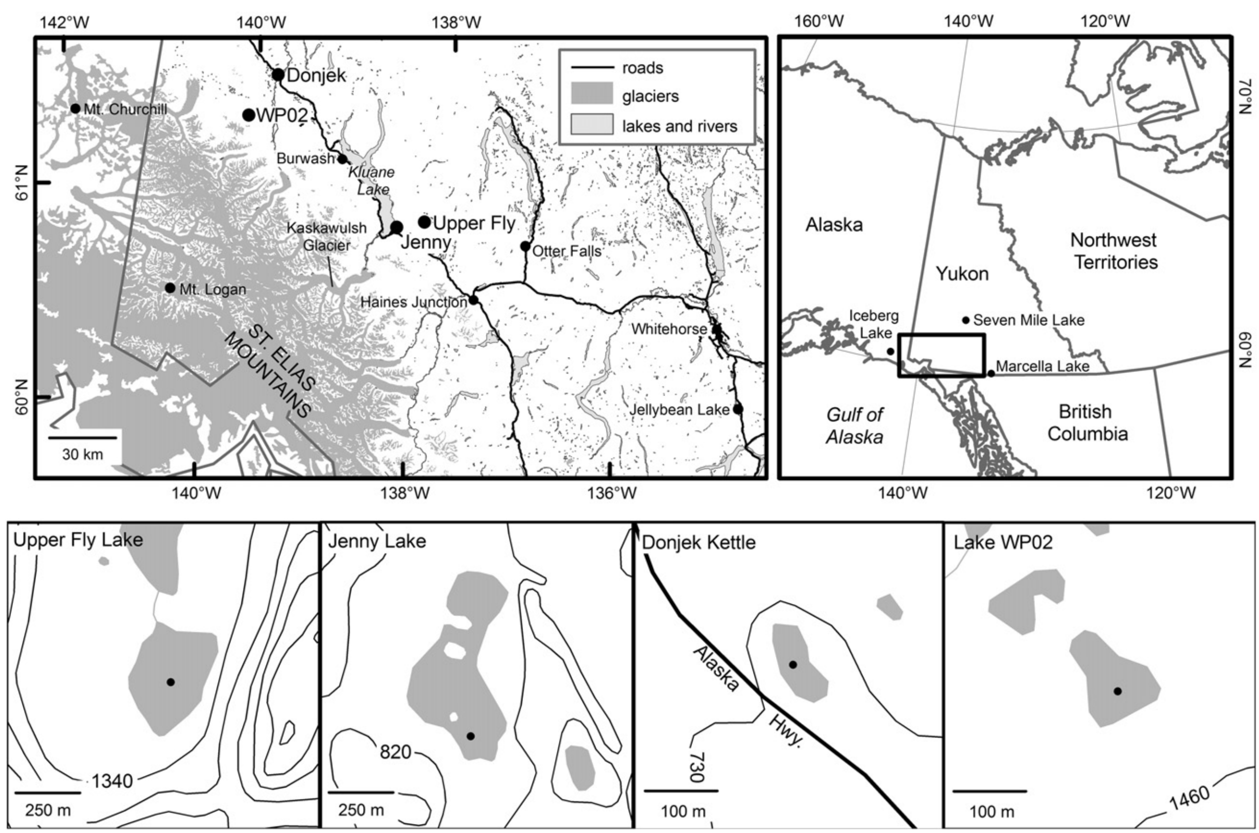

Figure 1. Location of Upper Fly Lake, Jenny Lake, Donjek Kettle, and Lake WP02, southwest Yukon Territory (large closed circles). Contour intervals on individual site maps are 30 m and coring sites are indicated. Other sites are mentioned in the text (small closed circles).

https://doi.org/10.1016/j.yqres.2012.01.002 Published online by Cambridge University Press

Methods

Field methods

Sediment cores were retrieved from each of the lakes using a clear plastic tube (5 cm diameter) fitted with a piston lowered to the sediment on drive rods. A 298-cm core was collected from Upper Fly Lake from a water depth of 4 m; only the uppermost 70 cm, spanning the past 1700 yr, were used for this study (see Bunbury and Gajewski, 2009a). Three cores of 164, 138 and 140 cm were collected from the deepest part of Jenny Lake (P. Johnson, personal communication) from a water depth of 4.2 m. One core was used to obtain material for radiocarbon dating, the second was used to extract chironomids and for determining sediment organic, carbonate, and biogenic silica content of the sediment, and the third was used to extract ostracodes. These cores were correlated using the peak in magnetic susceptibility corresponding to the White River Ash event (Bunbury and Gajewski, 2009b). The Jenny Lake record spans the past 3100 yr. A 147-cm lake sediment core was collected from Donjek Kettle from a depth of 6 m. The uppermost 102 cm, spanning the past 2200 yr were used in this study. A 38-cm sediment core covering the past 1200 yr was collected from Lake WP02 from a depth of 4.3 m. The uppermost sediments of all cores were extruded into plastic bags or bottles, at either 0.5- or 1.0-cm intervals in the field. The remaining sections of the cores were wrapped in plastic wrap and aluminum foil and returned to the lab at the University of Ottawa, Ontario where they were stored at 4°C.

Laboratory methods

Core chronologies were determined using ^{210}Pb, accelerator mass spectrometry (AMS) radiocarbon dating (^{14}C), and the ages of the tephra layers at AD 803 (Clague et al., 1995), and at 4 BC (Lowdon and Blake, 1968) at Donjek Kettle (Tables 1, 2 and 3; Fig. 2). Lead-210 was measured using alpha spectrometry on radiation emitted by ^{210}Po at Flett Research Ltd. (Winnipeg, Manitoba). A constant rate of supply (CRS) model was used with the ^{210}Pb analysis to compute the ages of the sediments with measurable ^{210}Pb activity for Upper Fly Lake, Jenny Lake and Donjek Kettle, and a linear regression model was applied to values from Lake WP02. Radiocarbon ages on terrestrial and aquatic macrofossils that were separated from the sediment by hand were provided by Beta Analytic Ltd. (Miami, Florida), and were calibrated using the IntCal09 calibration dataset (Reimer et al., 2009) and CALIB 6.0.1 (Stuiver et al., 1993).

Organic and carbonate contents of the sediments were determined using loss-on-ignition (LOI) at 550°C (4 h) and 950°C (2 h), respectively (Heiri and Lemcke, 2001). Biogenic silica (BSi) was extracted using a wet-alkali digestion technique and measured with a spectrophotometer (DeMaster, 1981; Parsons, 1984). Duplicate samples of known BSi content provided by an inter-laboratory study (Conley, 1998) were incorporated into each extraction batch to ensure laboratory experimental control. For the Upper Fly Lake sedimentary data, a subset of the LOI records used in Bunbury and Gajewski (2009a) were also used here, and 11 previously published BSi measurements were combined with 46 new measurements.

Between 1 and 16.8 cm^3 wet sediment from all sites was analyzed for chironomid head capsules at intervals between 1 and 4 cm. At Upper Fly Lake, 36 new levels were added to the 14 previously published chironomid samples from this time period in Bunbury and Gajewski (2009a). Where possible, ≥50 chironomid head capsules were identified at each level (cf. Heiri and Lotter, 2001); however, in a number of instances fewer were extracted due to low concentrations and depleted sediment. Head capsules were picked with forceps from a Bogorov sorting tray, dried on a coverslip and mounted using Entellan© (Walker, 2001). Taxa were identified under 200–400× magnification primarily using Wiederholm (1983) with additional reference to Barley (2004), Larocque and Rolland (2006), and Brooks et al. (2007). Types incorporated into the "Other Tanytarsina" group included *Tanytarsus lugens*-type, *Paratanytarsus* spp., and *Tanytarsus* and *Micropsectra* types that were worn and/or poorly preserved and could not confidently be identified further. Chironomid data are presented as percentages; taxa present in ≤2 samples or ≤2% abundance are considered rare and grouped into "Other Chironomidae" with unidentifiable and unknown head capsule counts.

Ostracodes were abundant in Jenny Lake sediments, present infrequently and in low abundance in Donjek Kettle sediments, and absent from Lake WP02 and Upper Fly Lake sediments of the past 2000 yr (see Bunbury and Gajewski, 2009a). Therefore, ostracodes were only analyzed from Jenny Lake sediments. Between 2.0 and 19.8 cm^3 of sediment was subjected to approximately three freeze–thaw cycles (Griffiths and Holmes, 2000) and sieved through 50-μm Nitex© mesh, and adult valves were picked from the sediment using a 0/5 brush under 10× magnification. Ostracodes were present in all 55 levels evaluated, and identifications were made under 20–40× magnification following (Delorme 1970a, b, c, d, 1971). These data are also presented as percentages.

Data analysis

Detrended correspondence analysis (DCA) was performed using CANOCO 4.5 (ter Braak and Šmilauer, 2002) on square-root-transformed chironomid percentage data matrices of 13 taxa and 50 samples for Upper Fly Lake, 18 taxa and 55 samples for Jenny Lake, 18 taxa and 40 samples for Donjek Kettle, and 18 taxa and 27 samples for Lake WP02, using detrending by segments and non-linear rescaling of axes. The ostracode data matrix of Jenny Lake contained nine species and 55 samples; data were log-transformed and rare taxa were downweighted to reduce their influence in the ordinations.

Table 1
^{210}Pb ages (at bottom of sediment section) from four lake sediment cores, southwest Yukon Territory computed using CRS (Upper Fly Lake, Jenny Lake, Donjek Kettle) and linear regression (Lake WP02) models. AT = alpine tundra site, BF = boreal forest site. The year of core collection is: Upper Fly Lake AD 1997, Jenny Lake AD 2003, Donjek Kettle and Lake WP02 AD 2006.

Depth (cm)	^{210}Pb total activity (Bq/g)	Yr before present	Yr AD	Depth (cm)	^{210}Pb total activity (Bq/g)	Yr before present	Yr AD
Southeast sites Upper Fly (AT)				Jenny (BF)			
3.0–4.0	15.54	6.8	1990	0.0–1.0	9.62	10.0	1993
4.0–5.0	12.80	13.7	1983	1.0–2.0	7.42	28.2	1975
5.0–6.0	10.48	20.3	1977	2.0–3.0	4.59	55.4	1948
6.0–7.0	8.93	27.6	1969	3.0–4.0	1.50	81.0	1922
7.0–8.0	6.77	32.9	1964	4.0–5.0	0.57	109.2	1894
8.0–9.0	5.53	38.4	1958	5.0–6.0	0.25		
9.0–10.0	4.16	42.8	1954	6.0–7.0	0.09		
10.0–11.0	3.35			7.0–8.0	0.01		
14.0–15.0	2.25						
19.0–20.0	1.80						
24.0–25.0	1.81						
Northwest sites Donjek (BF)				WP02 (AT)			
0.0–0.5	9.61	1.0	2005	0.0–0.5	29.74	0.5	2005
0.5–1.0	13.61	4.7	2001	0.5–1.0	31.57	2.7	2003
1.0–1.5	10.08	10.4	1996	1.0–1.5	26.92	8.2	1998
1.5–2.0	7.94	16.9	1989	1.5–2.0	21.62	15.5	1990
2.0–2.5	7.94	25.7	1980	2.0–2.5	17.29	23.9	1982
2.5–3.0	6.62	36.6	1969	2.5–3.0	11.90	33.6	1972
3.0–3.5	4.42	45.8	1960	3.0–3.5	10.44	44.3	1962
3.5–4.0	4.14	55.7	1950	3.5–4.0	7.52	55.2	1950
4.0–4.5	3.3	64.0	1942	4.0–4.5	6.80	58.2	1948
4.5–5.0	2.77	73.4	1933	4.5–5.0	6.46	61.1	1944
5.0–5.5	2.36	82.0	1924	5.0–5.5	5.84	63.9	1942
5.5–6.0	1.75						
6.0–6.5	1.71						
7.0–7.5	1.72						
8.0–8.5	1.72						
10.5–11.0	1.89						

https://doi.org/10.1016/j.yqres.2012.01.002 Published online by Cambridge University Press

Table 2
AMS radiocarbon ages from four lake sediment cores, southwest Yukon Territory. AT = alpine tundra site, BF = boreal forest site. Ages in italics were not used in the chronology development, see text. *Material other than twigs may be a combination of terrestrial and aquatic. Calibration was based on IntCal09 (Reimer et al., 2009).

Lake	Depth (cm)	Lab code	Conventional radiocarbon age (^{14}C yr BP)	2-sigma calibrated age range (cal yr AD)	Yr AD/yr BC (−)	δ^{13}C (‰)	Material*
Southeast							
Upper Fly (AT)	34.0–36.0	Beta − 229092	1490 ± 40	530–648	590	−26.3	Macrofossils
	69.0–71.0	Beta − 229093	2440 ± 40	−598–406	−543	−22.2	Macrofossils
Jenny (BF)	*31.5–34.5*	*Beta − 256717*	*2070 ± 40*	*−195–5*	*−90*	*NA*	*Macrofossils*
	69.5–71.5	Beta − 255709	1040 ± 40	893–1043	996	−24.6	*Picea* twig
	105.0–107.0	Beta − 255710	1820 ± 40	85–259	191	NA	Twig, macrofossils
Northwest							
Donjek (BF)	*26.0–27.5*	*Beta − 255707*	*1350 ± 40*	*614–723*	*670*	*−34.2*	*Moss fragments*
	82.0–83.0	Beta − 255708	1820 ± 40	85–259	191	−33.8	Plant fragments
	96.0–98.5	Beta − 256716	2160 ± 40	−265–92	−220	NA	Macrofossils
WP02 (AT)	17.0–17.5	Beta − 255711	430 ± 40	1414–1522	1460	−29.4	Moss fragments
	36.5–38.0	*Beta − 255712*	*480 ± 40*	*1394–1475*	*1431*	*−29.5*	*Moss/plant fragments*

Inference models were developed to estimate mean July air temperature (TJul) from the fossil chironomid data using 145 modern sites from Barley et al. (2006), 39 sites from Wilson and Gajewski (2004), and an additional two sites from Bunbury and Gajewski (2008). This resulted in a new chironomid calibration dataset containing 186 samples, 74 species, and 17 environmental variables. Rare taxa elimination, environmental variable selection, environmental data transformations, and model development followed Barley et al. (2006). A detrended correspondence analysis (DCA) performed on the species data revealed a gradient length of 3.63 (SD units), therefore a canonical correspondence analysis (CCA) was applied to determine the variables that best explain the variance in the chironomid data (CANOCO 4.5; ter Braak and Šmilauer, 2002). Initial CCAs were performed to assess colinearity among the variables, and to identify possible outliers. The variable "FOREST" had a variance inflation factor >20, and lakes A07, A25, U27, U58, KW03, and KW14 had extreme influence (>8×) as determined by the leverage diagnostics in CANOCO 4.5. Therefore, this variable and these sites were not included in the final ordination or in the development of the inference model. TJul, Depth, specific conductance (Cond), and dissolved organic carbon (DOC) were the four statistically significant ($p \leq 0.05$; 500 Monte Carlo permutations; in order of importance) variables that best explained chironomid species distribution. Weighted averaging regression and calibration (WA) was used to determine the TJul optimum for each taxon; these are presented in Fig. 3. A weighted averaging partial least squares (WAPLS) 2-component model produced the optimum model for TJul (Table 4).

Two methods were employed to determine how well the subfossil chironomid assemblages were represented in the modern training set. The first was to measure the dissimilarity between the assemblages in the modern training set and the subfossil assemblages using the squared chord distance and the best analogue (SCD; Overpeck et al., 1985), and the second was to passively plot the subfossil assemblages from each sediment core with those in the modern calibration set using a canonical correspondence analysis (CCA; Birks et al., 1990).

Table 3
References, radiocarbon ages, and errors of the two White River Ash tephra layers (WRA and WRA2).

Tephra	Reference	Conventional radiocarbon age (^{14}C yr BP)	2-sigma calibrated age range (yr AD)	Yr AD/Yr BC (−)
WRA	Clague et al. (1995)	Several	694–936	803
WRA2	Lowdon & Blake (1968)	1990 ± 130	−265–259	−4

Results

Chronologies

For all sites, the chronologies were established by linear interpolation between age determinations. At Upper Fly Lake a correction was applied to the two ^{14}C ages (Table 1) as follows. First, a linear regression was computed on the seven ^{14}C dates from the entire 298-cm lake sediment core (intercept a = 885 yr; see Bunbury and Gajewski 2009a); and a second was computed on the seven ^{210}Pb dates and the date of the WRA (intercept b = 195 yr; Tables 1 and 2). The difference between the intercepts was interpreted as a hard-water effect and a correction of 690 yr (i.e., 885 yr–195 yr) was applied to the two ^{14}C dates used in this chronology, as done, for example, by Peros and Gajewski (2009). The chronology was therefore established by linear interpolation between the seven ^{210}Pb dates, two corrected ^{14}C dates, and the date of the WRA (Fig. 2a). This hard-water correction was not needed at the other sites. Two ^{14}C ages, five ^{210}Pb ages, and the age of the WRA were used to assign ages to the Jenny Lake sediment core (Tables 1, 2 and 3; Fig. 2b). Although a third ^{14}C age was available, it was rejected, as it was located stratigraphically above the WRA but was considerably older. Three ^{14}C ages, 11 ^{210}Pb ages and two White River tephras (WRA and WRA2) were available from Donjek Kettle; however, one of the ^{14}C ages located above the WRA was older than the ash and was rejected (Tables 1, 2 and 3; Fig. 2c). The final chronology was based on 11 ^{210}Pb ages, two ^{14}C ages, and the ages of the two tephras. At Lake WP02, one ^{14}C age and 11 ^{210}Pb ages were used to establish the chronology; a second ^{14}C age was rejected as it was located at the top of the WRA yet was considerably younger (Tables 1, 2 and 3; Fig. 2d). Ages on all graphs are presented as yr AD or BC.

Chironomid and ostracode assemblages

Sergentia was present during the late Holocene at Upper Fly Lake, Donjek Kettle and Lake WP02, but absent from Jenny Lake (Fig. 3). The combined group of Other Tanytarsina types occurred at all sites, although in much lower abundance after ~AD 1150 at Donjek Kettle. *Chironomus anthracinus*-type, which had a warmer TJul optima (based on our modern calibration dataset, see Methods section) than both Other Tanytarsina and *Sergentia*, was found throughout the cores at Upper Fly Lake, Jenny Lake, and Donjek Kettle, (Figs. 3a, b, c) however it was less abundant at Upper Fly Lake and absent from Lake WP02 where taxa with the coldest TJul optima were encountered (Fig. 3d). *Cricotopus*/*Orthocladius* was a dominant taxon at Upper Fly Lake and occurred frequently

https://doi.org/10.1016/j.yqres.2012.01.002 Published online by Cambridge University Press

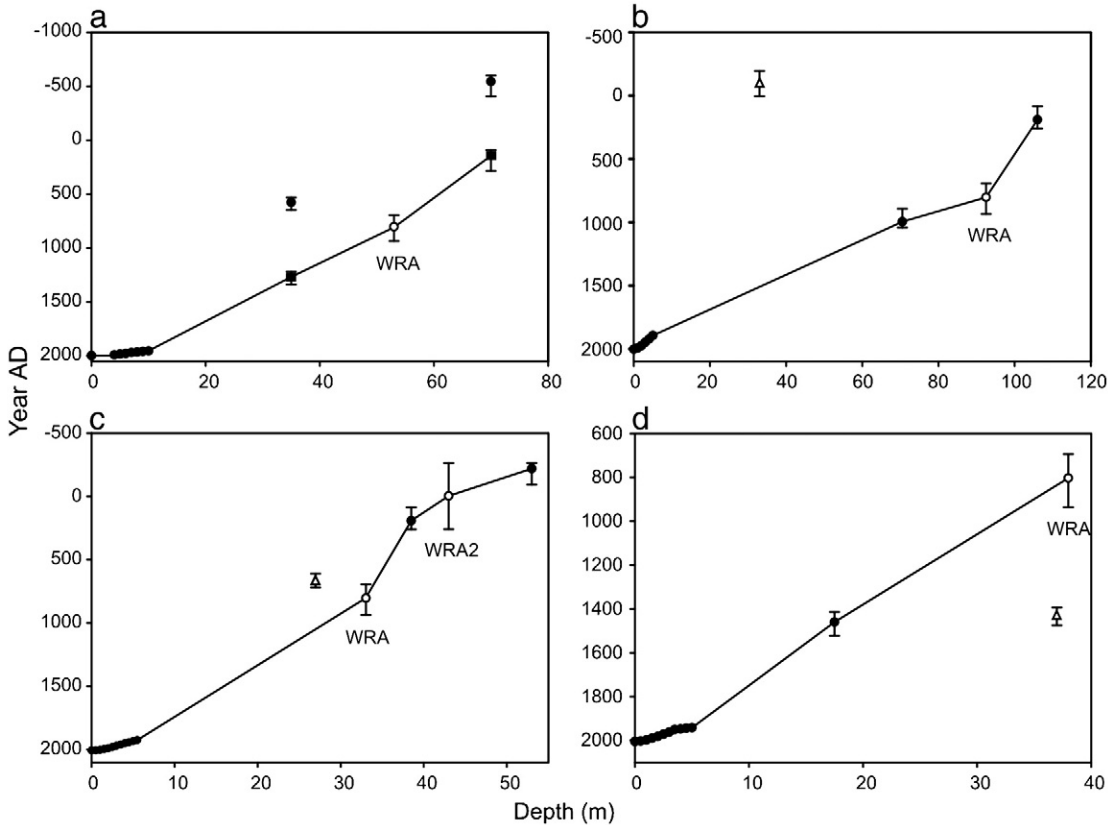

Figure 2. Sediment chronologies for (a) Upper Fly Lake, (b) Jenny Lake, (c) Donjek Kettle, and (d) Lake WP02, southwest Yukon Territory. The solid circles are ^{210}Pb and uncorrected ^{14}C ages, the triangles are discarded ages, the open circles indicate the depths and ages of the White River Ash (WRA; Clague et al., 1995) and (WRA2; Lowdon and Blake, 1968), and the solid squares are corrected ages.

throughout the core at Jenny Lake; however, this group was much less abundant at Donjek Kettle or Lake WP02.

Taxa with colder TJul optima (*Sergentia* and *Cricotopus*/*Orthocladius*) dominated the assemblages at Upper Fly Lake, but not at the other three sites, where combinations of taxa with warm and cold optima were abundant (Fig. 3). At Jenny Lake, the group Other Tanytarsina and *C. anthracinus*-type dominated. These taxa were also important at Donjek Kettle, however, Other Tanytarsina types were abundant before ~AD 1150 and C. *anthracinus*-type subsequently (Fig. 3c). Profundal taxa (*Sergentia* and *Procladius*) were also present at this site. Several taxa were abundant at Lake WP02 with *Micropsectra*, Other Tanytarsina and *Zalutschia lingulata*-type occurring throughout the record, *Corynocera ambigua* prior to about AD 1200, and *Zalutschia* type B between approximately AD 1450 and 1950. *Zalutschia* spp. were abundant only at this site.

Taxa found at alpine tundra sites (Upper Fly Lake and Lake WP02; Figs. 3a, d) had a broader range of TJul optima (5.8°C and 6.1°C, respectively) compared to sites in the boreal forest (Jenny Lake 4.1°C and Donjek Kettle 3.8°C; Figs. 3b, c), although the maximum thermal optimum was similar among all sites (12.9° to 13.2°C). Taxa with the coldest temperature optima (*Hydrobaenus*/*Oliveridia* and *Paracladius*), were encountered only at the tundra sites (Figs. 3a, d). Little similarity existed between the taxa found at the two boreal sites however the fauna at Jenny Lake consisted of several genera from the tribe Chironomini that have higher temperature optima (Figs. 3b, c).

Nine ostracode species were identified from the sediment core collected from Jenny Lake (Fig. 4). *Candona acutula* and *Candona candida* showed inverse tendencies through time, whereas *Candona decora* generally co-occurred with *C. candida*, and *Cyclocypris ampla* with *Cypridopsis vidua*. Ostracodes were not found in the late-Holocene sediments of the other sites, although Bunbury and Gajewski (2009a) encountered ostracodes in late-glacial and early-Holocene sediments of Upper Fly Lake.

Ordinations

Detrended correspondence analyses (DCA) revealed comparable gradient lengths on axis 1 (Upper Fly Lake = 1.7 standard deviation (SD) units; Jenny Lake = 1.8 SD units; Donjek Kettle = 1.9; WP02 = 2.1); these values suggest that the chironomid compositional turnover (ter Braak, 1995) during the late Holocene was relatively low. The variances explained by DCA axis 1 were higher at the two northwest sites (Donjek Kettle $\lambda_1 = 0.25$; Lake WP02 $\lambda_1 = 0.24$) than at the southeast sites (Upper Fly and Jenny lakes $\lambda_1 = 0.20$), whereas the variances explained by DCA axis 2 were higher at sites in the boreal forest (Jenny Lake and Donjek Kettle $\lambda_2 = 0.10$) than those located in alpine tundra (Upper Fly Lake $\lambda_2 = 0.06$; Lake WP02 $\lambda_2 = 0.07$; Figs. 5a–d). A wide variety of taxa exhibited high positive or negative loadings on DCA axes 1 and 2 at all four sites, including warm-adapted (e.g., *C. anthracinus*-type, *Dicrotendipes*, *Procladius)* and cold-adapted types (e.g., *Cricotopus*/*Orthocladius*, *Heterotrissocladius* spp., and *Corynocera oliveri*-type) that were found in either profundal (e.g., *Procladius* and *Sergentia*) or littoral (e.g., *Dicrotendipes* and *Microtendipes*) areas of the lake. In addition, some taxa are known to have a preference for organic sediments (e.g., Other Tanytarsina and *Psectrocladius* spp.), whereas others prefer more minerogenic substrates (e.g., *C. anthracinus*-type and *Micropsectra* spp). Therefore, interpreting the environmental gradients associated with the first and second axes at each of the sites is not straightforward.

The ostracode data revealed a slightly longer gradient length than was found with the chironomid data (2.4 SD units). A large portion of the

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variance was explained by the first two axes (Fig. 5e), a result of the lower diversity in the ostracode fauna. *C. decora*, *Ilyocypris bradyi* and *C. vidua* are correlated with DCA axis 1, whereas *C. decora* is positively and *I. bradyi* negatively correlated with DCA axis 2. This suggests that DCA axis 1 is related to the magnesium–calcium ratio of the lake water, whereas axis 2 is a conductivity gradient (Bunbury and Gajewski, 2005).

The sample-score time series differed between sites, with the most pronounced changes occurring on the chironomid DCA axis 1

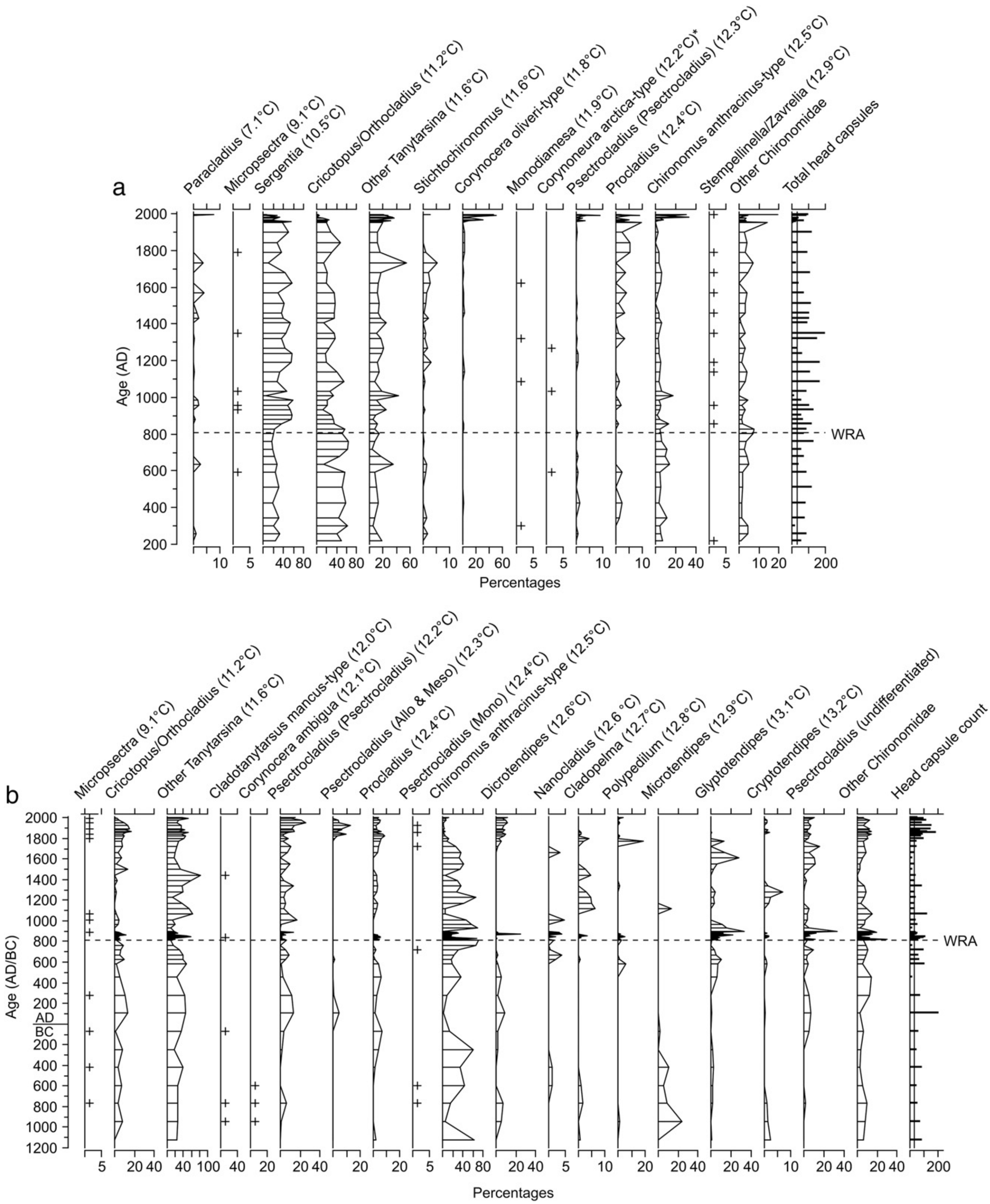

Figure 3. Relative abundance of chironomid taxa from (a) Upper Fly Lake, (b) Jenny Lake, (c) Donjek Kettle, and (d) Lake WP02, southwest Yukon Territory. Taxa are organized by mean July air temperature optima computed from a modern training set using weighted averaging regression and calibration; types denoted with an asterisk are based on the temperature optima of the genus. Taxa with ≤5 occurrences or ≤5% abundance are represented by crosses. The dashed horizontal lines represent the timing of the White River Ash (AD 803) and the White River Ash 2 at Donjek Kettle (4 BC; Table 3). AT = alpine tundra site, BF = boreal forest site. Note different scales on the x and y axes.

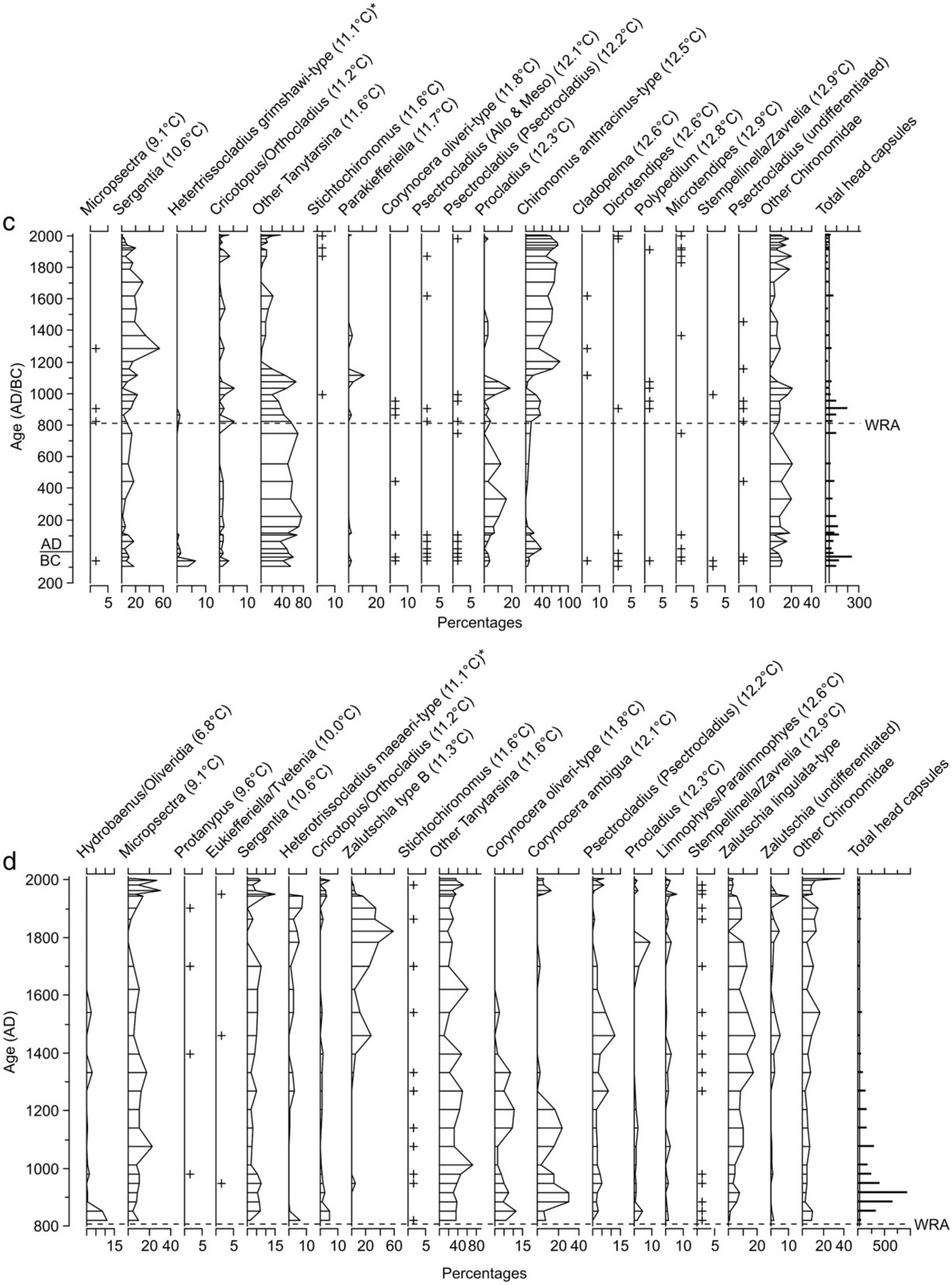

Figure 3 (*continued*).

at Upper Fly Lake after AD 1950 and on axis 2 after AD 1750 (Fig. 6a). At Jenny Lake, deviations to lower scores occurred after AD 1650 on both chironomid and ostracode DCA axis 1 (Fig. 6b). Sample scores on DCA axis 1 at Donjek Kettle decreased after AD 1050, and increased at Lake WP02 after AD 1800 (Figs. 6c, d).

Sediment stratigraphy

The sediment cores from the two alpine tundra sites (Upper Fly Lake and Lake WP02; Figs. 6a, d) were composed of dark brown gyttja and generally showed higher LOI550 values (25–37% and 4–29%,

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Table 4
Performance statistics of the chironomid weighted-averaging partial-least-squares (WAPLS) 2-component model used to reconstruct mean July air temperature (TJul) at four sites in the southwest Yukon Territory.

Variable	r^2_{boot}	Max $bias_{boot}$	RMSEP
TJul	0.69	2.9°C	1.7°C

respectively), than the two sites located in the boreal forest (Jenny Lake <19% and Donjek Kettle <16%; Figs. 6b, c). The Jenny Lake sediment core consisted of plain gray marl, whereas the Donjek Kettle core was dark brown and contained fine-grained clastic material. Values of biogenic silica (BSi) were higher at sites located in alpine tundra (up to 24% in Upper Fly Lake, and 60% in Lake WP02) than those in the boreal forest (Jenny Lake up to 13%; Donjek Kettle up to 8%). Carbonate content was higher in the Jenny Lake core than at the other sites.

Chironomid-inferred mean July air temperatures

The squared chord distances (SCD) quantifying the dissimilarity between the fossil and modern (best analogue) samples were slightly higher at Donjek Kettle and Lake WP02 than at Upper Fly and Jenny lakes (Fig. 6). At Upper Fly Lake, the subfossil chironomid assemblages ordinated with cooler, deeper lakes in the modern training set (Fig. 7a) whereas chironomid assemblages from the Jenny Lake core resembled those from shallow lakes with higher conductivity values (Fig. 7b). Some of the chironomid samples from the Donjek Kettle core were plotted more closely to lakes that are deeper and/or have slightly higher dissolved organic carbon values (Fig. 7c), whereas the down-core assemblages from Lake WP02 (Fig. 7d) were more similar to those encountered in deeper and/or cooler lakes in the modern set. These analyses show that the subfossil samples generally resembled samples in the modern dataset, with the exception of three levels at Lake WP02 that occurred during the Little Ice Age.

CCAs constrained to TJul revealed a strong relation existed between chironomids and TJul ($\lambda_1/\lambda_2 = 0.98$), and that a robust inference model could be developed for this variable (ter Braak and Prentice, 1988). Ranges of the reconstructed TJul were similar at sites in the boreal forest (Jenny Lake = 10.5 to 13.1°C, Donjek Kettle = 10.5 to 12.8°C; Figs. 6b, c), and although minimum TJul values were comparable at the two alpine sites, maximum values differed (Upper Fly Lake = 9.2 to 11.1°C, Lake WP02 = 9.6 to 14.5°C; Figs. 6a, d). TJul reconstructions from Upper Fly and Jenny lakes resemble each other, with cool periods centered on AD 1900, 1400 and 1000 and generally between AD 200 and 800. At the two northern sites, estimates suggest an overall warming over the past 1200 yr, however, the Donjek Kettle record has fewer samples in this portion of the record, and at Lake WP02, warmer TJul from AD 1750 to 1850 were reconstructed with samples that had high squared chord distances, and were located outside of the ordination space of the modern training set (Figs. 6d and 7d), suggesting non-analogue assemblages. This is a reflection of the dominance of the genus *Zalutschia* in the assemblages at this time; *Zalutschia* type B is under-represented in the modern data (up to 11%) compared to the fossil (24–37%), and the abundant *Z. lingulata*-type was not present in modern samples (Figs. 3d, 7d).

Discussion

Between AD 200 and 600, the reconstructions at Upper Fly Lake, Jenny Lake and Donjek Kettle generally show relatively low mean July air temperatures. These remained low until AD 1000 at Upper Fly Lake and Donjek Kettle whereas they increased to present-day values by AD 600 at Jenny Lake. The record does not extend to this time at Lake WP02. Glacial advances in coastal and near-coastal British Columbia and Alaska between AD 200 and 700 (Reyes et al., 2006a) and also in the interior St. Elias Mountains from AD 700 to 900 (Denton and Karlén, 1973) correspond with this cooler period. Summer air temperatures at Iceberg Lake in Alaska (Loso, 2009) suggest cooler, but variable conditions from AD 400 to 1000.

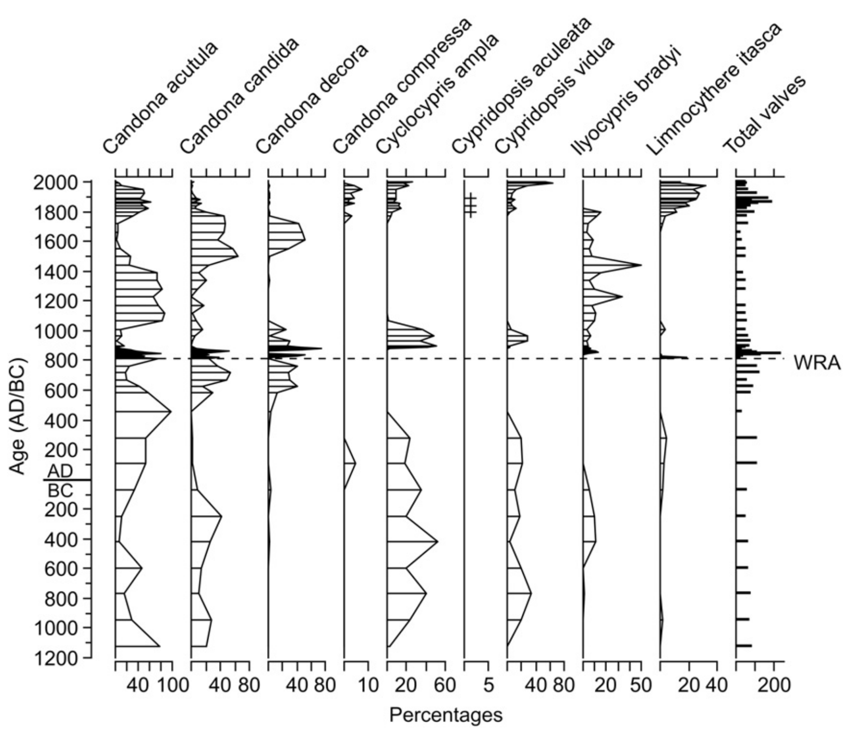

Figure 4. Relative abundance of ostracode taxa (presented alphabetically) from Jenny Lake, southwest Yukon Territory. The dashed horizontal line represents the timing of the White River Ash. Note different scales on the x-axis.

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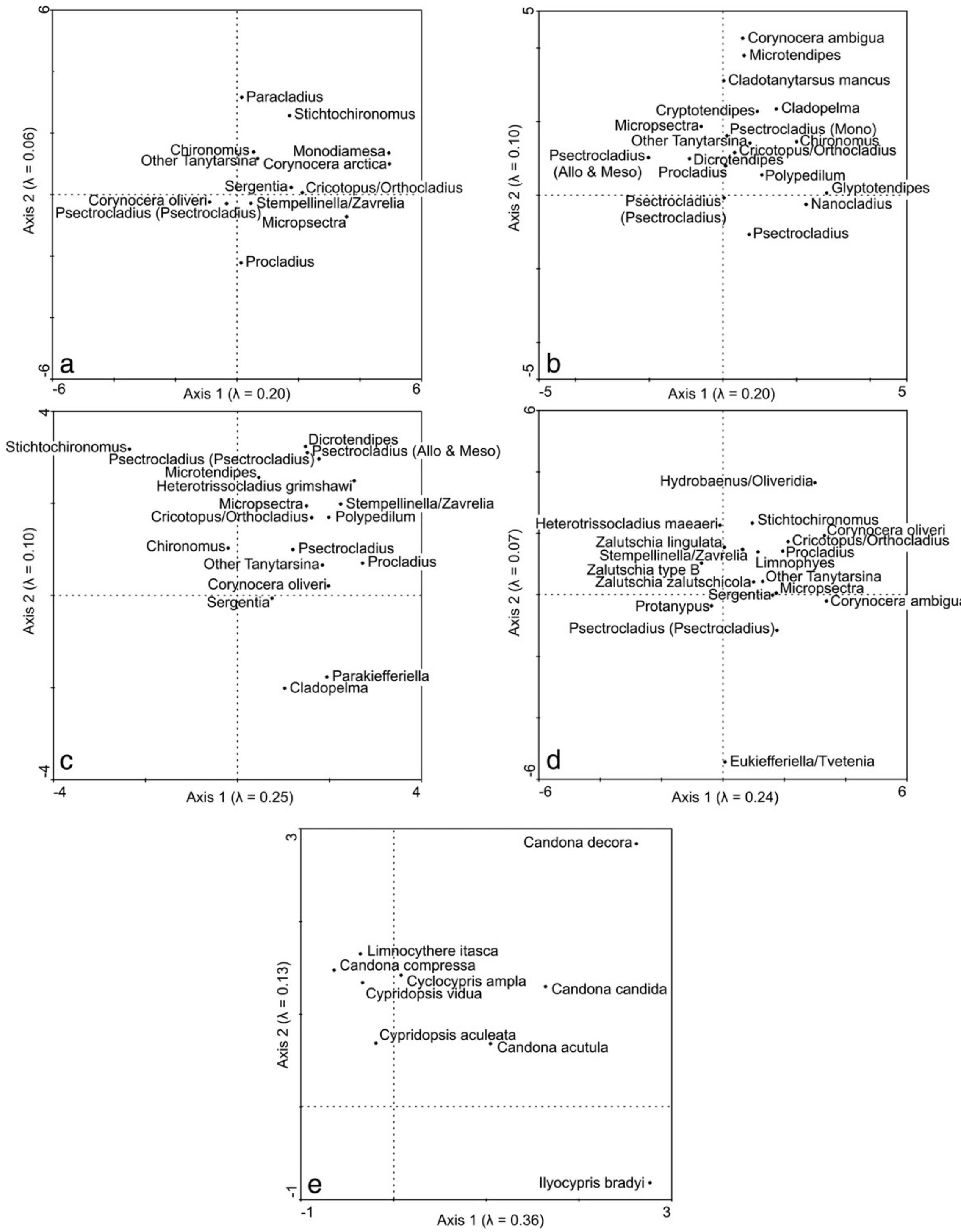
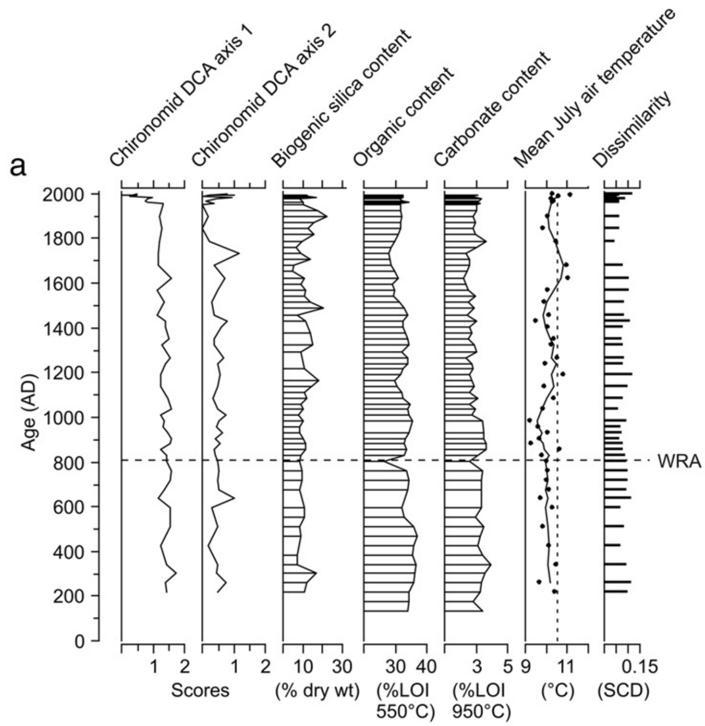


Figure 5. Detrended correspondence analysis plots of chironomid taxa from (a) Upper Fly Lake, (b) Jenny Lake, (c) Donjek Kettle, (d) Lake WP02, and (e) ostracode taxa from Jenny Lake, southwest Yukon Territory.

The temperatures reconstructed for Jenny Lake between AD 600 and 1000 may have been confounded in part by changes in regional groundwater fluctuations and the level of the much larger Kluane Lake. Jenny Lake is situated on a till bed ~1.5 km east of Kluane Lake and regional groundwater level fluctuations today influence water levels at the smaller lake (personal observation). Brahney et al. (2008) inferred lake-level variations based on geochemical data derived from Kluane Lake sediments, and interpreted that they were caused by climate and glacier fluctuations. Between AD 650 and 1050, Kluane Lake levels were higher, thereby influencing the water level at Jenny Lake. The profundal-dwelling *C. anthracinus*-type (Brooks et al., 2007) is abundant during the time in question, and also has a warmer temperature optimum, resulting in the reconstruction of warmer conditions. In addition, primary production was low (indicated by lower biogenic silica values), which would also imply deeper water.

Temperature estimates from Upper Fly Lake, Jenny Lake and Lake WP02 suggest relatively warm conditions between AD 1100 and 1400; there are few samples in the Donjek Kettle record during this time (Fig. 6). Warmer temperatures increased production (as indicated by increased biogenic silica and organic content at Upper Fly and Jenny lakes) and also induced changes in the chironomid and ostracode communities, particularly noticeable at Jenny Lake. This warming coincides with evidence of glacial retreat and treeline advance in the St. Elias Mountains between ~AD 900 and 1500 (Denton and Karlén, 1973), and slightly warmer conditions in the varve-inferred summer temperature record from Iceberg Lake (Loso, 2009). In contrast, early Little Ice Age glacial advances in Alaska and the Yukon Territory are thought to have been in response to cool, wet conditions between AD 1100 and 1300 (Anderson et al., 2011).

At Upper Fly and Jenny lakes, temperatures were generally cool between AD 1400 and 1900, although our estimates suggest that a period of warm temperatures occurred in the middle of this period. Lake production was reduced in response to the cooler temperatures (Figs.



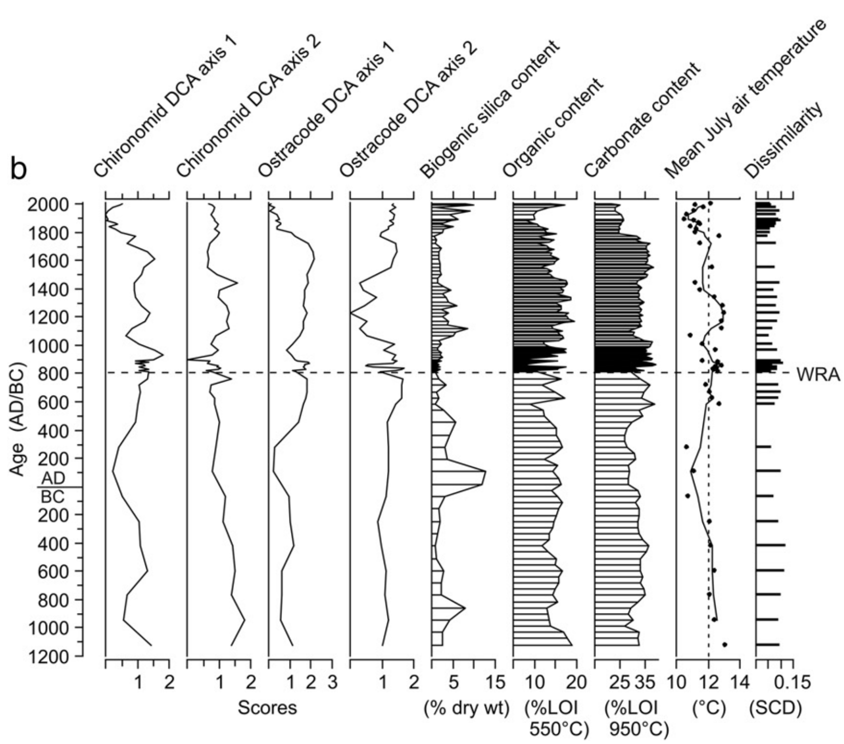


Figure 6. Detrended correspondence analysis (DCA) sample scores of chironomid taxa, biogenic silica, organic, and carbonate content of the sediments, chironomid-inferred mean July air temperatures with 3-point moving averages, and dissimilarity measures from (a) Upper Fly Lake, (b) Jenny Lake, (c) Donjek Kettle, and (d) Lake WP02, southwest Yukon Territory. DCA sample scores of ostracode taxa are also presented for Jenny Lake. The dashed vertical lines on the temperature curves represent the modern temperatures (Upper Fly Lake = 10.5°C; Jenny Lake = 12°C; Donjek Kettle = 11.6°C; Lake WP02 = 10.7°C) and the dashed horizontal lines represent the timing of the White River Ash (AD 803) and the White River Ash 2 at Donjek Kettle (4 BC). AT = alpine tundra site, BF = boreal forest site. Note different scales on the x and y axes.

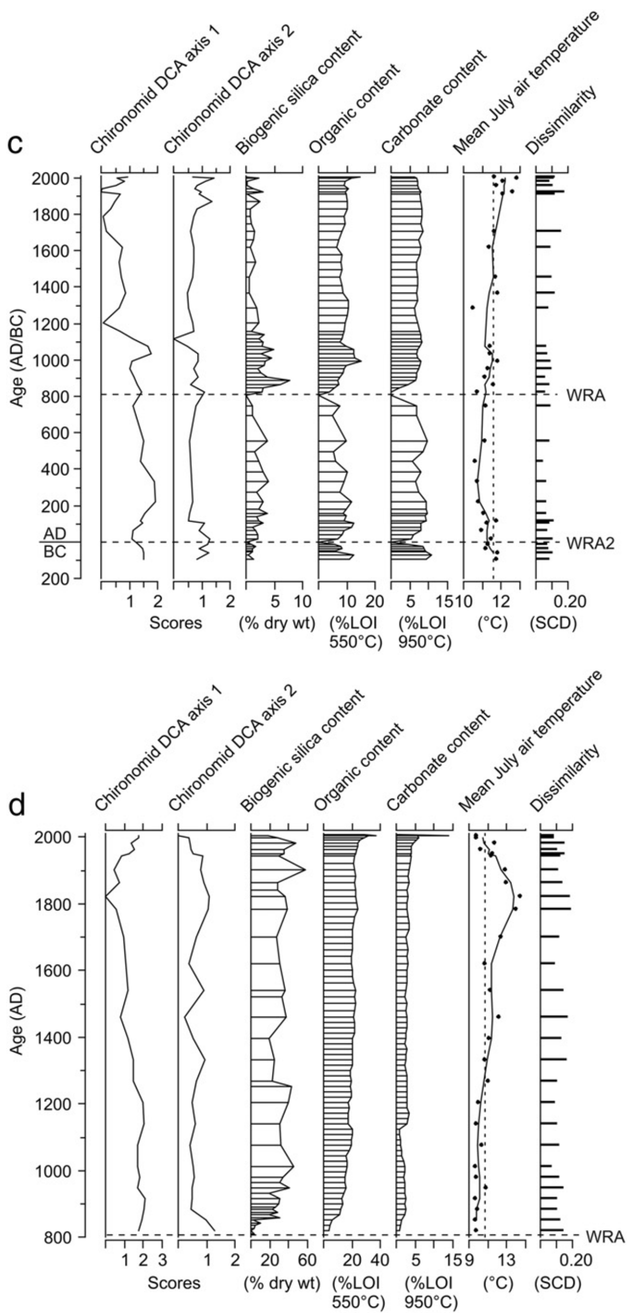


Figure 6 (continued).

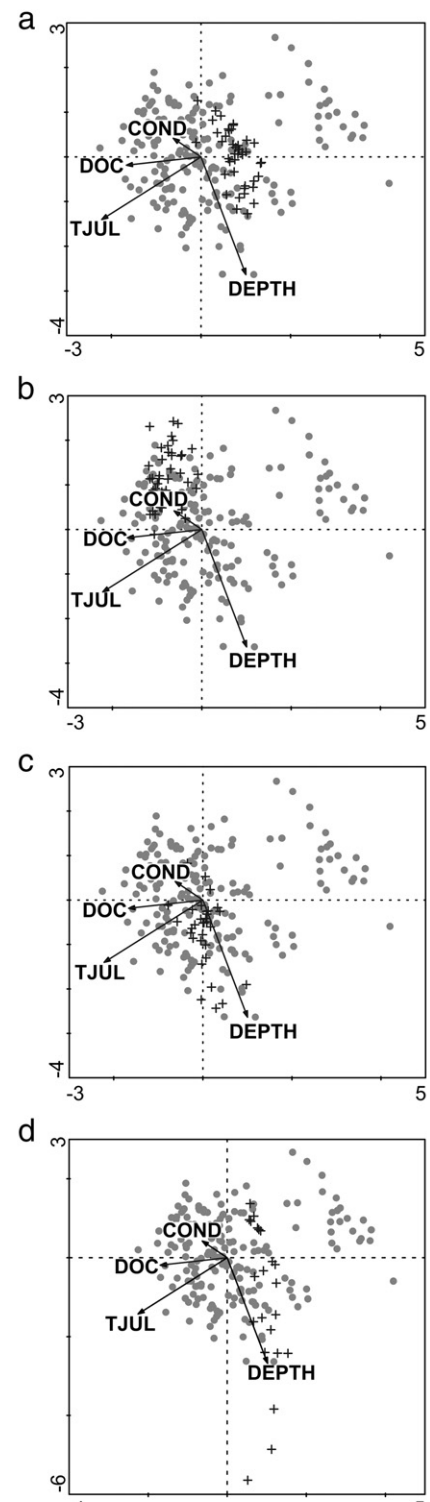


Figure 7. Canonical correspondence analysis biplots of sites in the modern calibration set (gray circles) plotted with passive subfossil samples (plus signs) and 4 statistically significant ($p \leq 0.05$) environmental variables (TJul = mean July air temperature, Depth = water depth, Cond = specific conductance, and DOC = dissolved organic carbon) from (a) Upper Fly Lake, (b) Jenny Lake, (c) Donjek Kettle, and (d) Lake WP02, southwest Yukon Territory.

6a, b). Poor analogues at Lake WP02 and lack of data points at Donjek Kettle make it difficult to comment on the warm temperature reconstructions from these sites during this time (Figs. 6c, d).

A considerable change in the chironomid and ostracode communities (DCA axis 1) and lake production was evident at Jenny Lake ~AD 1750. Water levels in the Kluane Lake region were reduced after the nearby Kaskawulsh Glacier reached its maximum Little Ice Age extent (Reyes et al., 2006b); this resulted in the high-stand of Kluane Lake and subsequent drainage reorganization to the north and reduction in water levels (Clague et al., 2006; Brahney et al., 2008). The chironomid community at Upper Fly Lake (DCA axis 2) was also affected; however, the mechanism for the response at this site is not as clear, as it is located at higher elevation and would not be influenced by fluctuations in Kluane Lake levels.

Lower temperatures at Upper Fly and Jenny lakes from AD 1750 to 1900 are coherent with cooler June–July temperatures inferred from tree-rings (Youngblut and Luckman, 2008) and varves at Iceberg Lake (Loso, 2009). At approximately AD 1840, there was an abrupt shift to more negative δ^{18}O values in both the Mt. Logan and Jellybean

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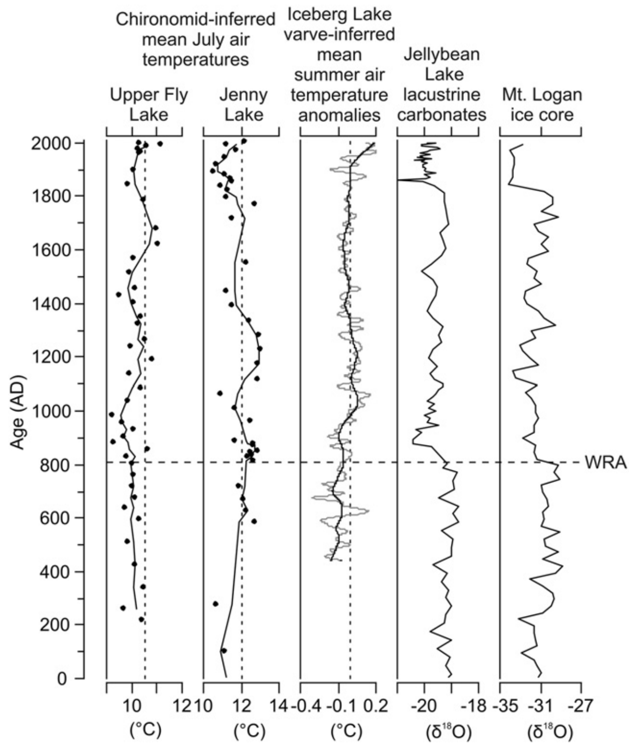

Figure 8. Chironomid-inferred mean July air temperature reconstructions from Upper Fly Lake and Jenny Lake, southwest Yukon Territory, varve-inferred summer temperature reconstruction from Iceberg Lake, Alaska (Loso, 2009), $\delta^{18}O$ of lacustrine carbonate from Jellybean Lake (Anderson et al., 2005), and $\delta^{18}O$ of the ice core from Mt. Logan (Fisher et al., 2008). See Figure 1 for locations of the records. The dashed horizontal line represents the timing of the White River Ash.

Lake records that has been interpreted as the end of the Little Ice Age in the region (Fig. 8; Fisher et al., 2004). About AD 1900, temperatures began to warm at Upper Fly and Jenny lakes and the considerable shift in the chironomid community from the former site to taxa with warmer temperature optima after ~AD 1950 (Figs. 3a, 6a) compares well with warmer summer temperatures inferred from Iceberg Lake varves and local tree-rings (Youngblut and Luckman, 2008; Loso, 2009).

The potential impact of Kluane Lake water-level fluctuations, changes in evaporation, and/or variations in precipitation all influence lake levels and ultimately the chironomid community, providing a challenge for establishing quantitative temperature estimates using these organisms in the southwest Yukon. However, the robust inference model, and the presence of good analogues at all sites except Lake WP02 lend confidence to our results. Our chironomid-inferred temperature estimates from the two southeast sites (Upper Fly and Jenny lakes) compare well with one another and also with other paleoclimate evidence from the region (Fig. 8). Between AD 200 and 1100, temperatures in the region were relatively cool, whereas the more reliable temperature records suggest relatively warm conditions during medieval times, centered on AD 1200, followed by a cool Little Ice Age, and warming temperatures over the past 100 yr.

Acknowledgments

We would like to thank P. Johnson, A. Viau, T. Lacourse, B. O'Neil and the students of GEG4001 (2003) for help in the field; L. Vasconcelos, B. O'Neil, A. Leduc, R. Ravindra, S. Bazinet, A. Valenius, J. McGuinness, L. Robert, A. Baxter and E. Drummond for help in the lab, and M.-C. Fortin and E. Barley for discussions regarding chironomid identifications. Research funding to Bunbury was provided by the Yukon Geological Survey, an endowment grant from the Northern Research Institute at Yukon College, and the Northern Scientific Training Program, and to Gajewski from the Natural Sciences and Engineering Research Council of Canada. We acknowledge the Centre for Global Change Science at the University of Toronto for funding during preparation of this manuscript. The Kluane Lake Research Station provided support in the field, and the Kluane and Champagne-Aishihik First Nations allowed access to their traditional territories to conduct this research.

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