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Application of a midge-based inference model for air temperature reveals evidence of late-20th century warming in sub-alpine lakes in the central Great Basin, United States

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ABSTRACT

Sediment cores were recovered from Stella Lake and Baker Lake, sub-alpine lakes located in Great Basin National Park, NV, in 2005 and 2007, respectively. The cores were analyzed for subfossil chironomid (Insecta: Diptera: Chironomidae) remains. Chronologies for the sediment cores, developed using ^{210}Pb, indicate the cores span the 20th century. The midge communities present in the lakes experience muted compositional change through much of the 20th century; however, the post-AD 1980 interval is notable due to rapid lake-specific faunal turnover. The recently deposited sediment in Baker Lake is characterized by decreases in the relative of abundance of *Psectrocladius semicirculatus/sordillelus*, *Cladotanytarsus mancus* group and *Procladius*, the local extirpation of *Chironomus*, and an increase the proportion of *Sergentia*, *Tanytarsus* type *G* and *Tanytarsus* type *B*. The Stella Lake midge community experienced a shift post-AD 1990 from an assemblage dominated by *Tanytarsus* type *G* to a *P. semicirculatus/sordillelus* dominated community. Application of a chironomid-based inference model for mean July air temperature (MJAT), based on a calibration set developed for the Inter-Mountain West of the United States consisting of 79 lakes and 54 midge taxa ($r^2_{\text{jack}} = 0.55$ °C, RMSEP = 0.9 °C, maximum bias = 1.66 °C), provided a means to reconstruct the 20th century temperature regime for the region. Stella Lake and Baker Lake experience large fluctuations in MJAT during the early to mid-20th century and consistently above average temperature during the late-20th century. The chironomid-inferred MJAT reconstructions for Stella Lake and Baker Lake track observed July temperature in the region encompassed by Nevada Climate Division #2 during the late-20th century.

1. Introduction

Climate models suggest that global surface temperatures will increase between 1.4 °C and 5.8 °C by AD 2100 and that mean sea-level will increase between 0.10 and 0.90 m during the same interval (Intergovernmental Panel on Climate Change, 2007). These global averages do not capture the inherent spatial variability that exists in the climate system; they pay little attention to the significant and differing responses that will occur at the regional level. Continental and regional-scale climate models have been developed for North America (North American Regional Climate Change Assessment Program, 2007; Seager et al., 2007) but the spatial resolution of these models may not be sufficient to accurately capture the climate dynamics associated with the complex topography of regions such as the Great Basin (Leung et al., 2003).

Freshwater resources in the Great Basin of the United States have come under increasing pressure due to a sustained drought (MacDonald, 2007) and rapid population growth (U.S. Census Bureau, 2008). Reduction in the base stream-flow of the Colorado River from 20 million acre feet per year at Lee's Ferry in 1995 to 9 million acre feet per year in 2004 (USBR, 2008) in conjunction with population growth has led the Southern Nevada Water Authority (SNWA) to turn its attention northward to the central Great Basin where a system of basin and range carbonate-rock aquifers exist. The proposed withdrawal of 200,000 acre feet of water will result in significant alterations to the eastern Great Basin's surface and sub-surface hydrology (Deacon et al., 2007). Changes to hydrology arguably comprise the most critical regional impact of global climate change to the Inter-Mountain West of the United States. Reconstructing the regional and sub-regional

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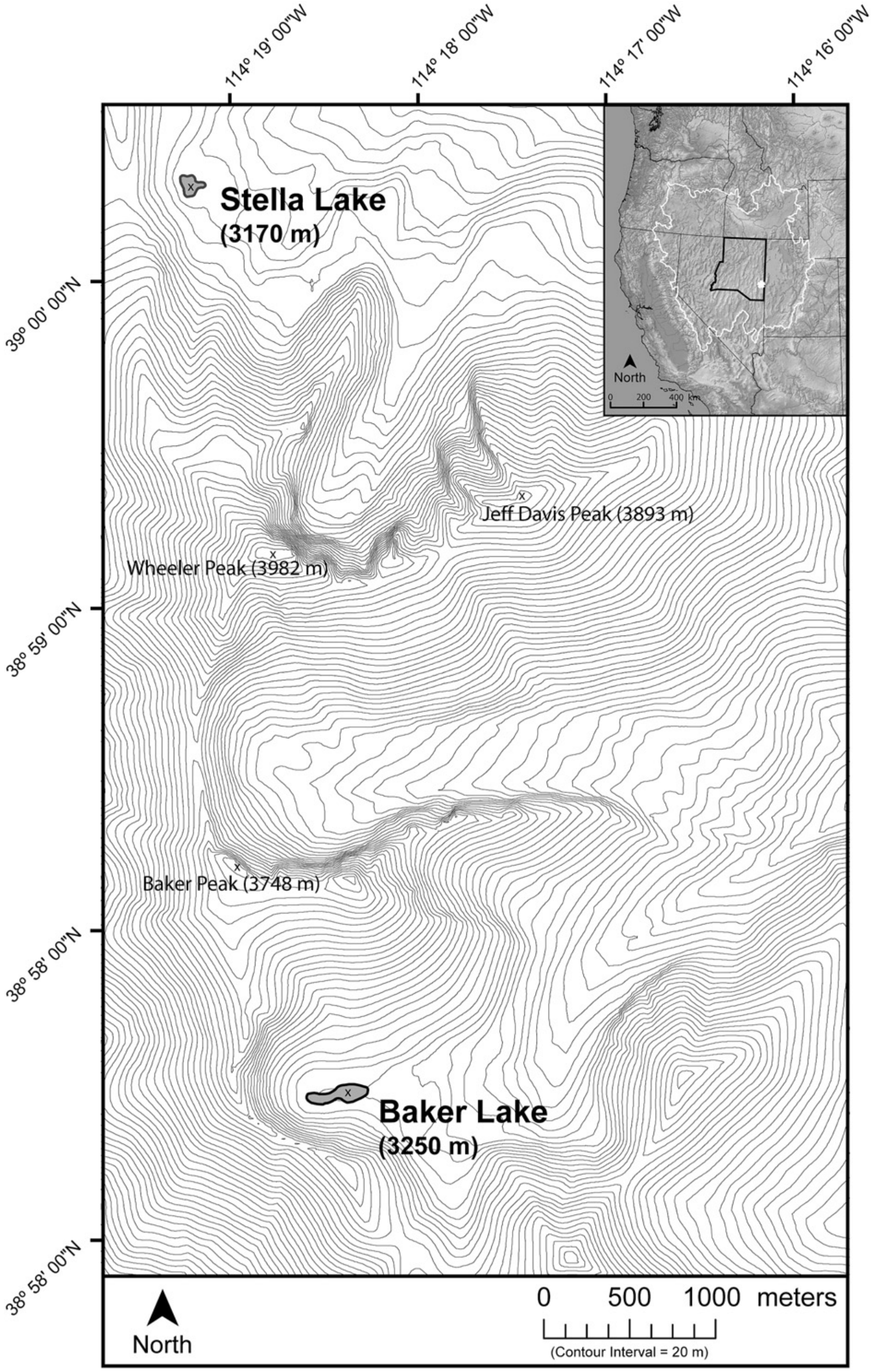

Fig. 1. Location of Stella Lake and Baker Lake. Great Basin National Park (GBNP) indicated by white circle. Inset Map: Area encompassed by Nevada Climate Division #2 outlined in black. Coring location indicated by X.

responses of Great Basin hydroclimatology to climate dynamics in the recent past, i.e. 21st and 20th centuries, and over the late Holocene (last 2000 years) will provide valuable insight to the nature of future local responses to climate change.

It is increasingly recognized that high-elevation and high-latitude regions are responsive and extremely sensitive to climate change (Smith et al., 2005; Smol et al., 2005; Westerling et al., 2006; Barnett et al., 2008). The increases in surface temperature that are projected to occur as a result of global warming will impact the chemical and physical limnology of high-altitude lakes as well as the biota currently present in these lakes (Melack et al., 1997; Wolfe et al., 2003; Nydick et al., 2004; Parker et al., 2008). However, alpine lakes, due to their remoteness, tend to be poorly monitored with limited faunal distributional data collected and few or no instrumental climate records available. Using a paleolimnological approach to study the modern distribution of aquatic fauna in high-elevation lakes will help to establish 'baseline' conditions against which the effects of projected warming in these regions can be

Table 1
Selected environmental characteristics of Stella Lake and Baker Lake measured at time of sediment collection.

Environmental variable	Stella Lake	Baker Lake
Elevation (m a.s.l.)	3150	3194
Depth (m)	2.50	1.60
Surface area (ha)	3.0	3.5
Secchi depth (m)	Unlimited	Unlimited
pH	7.23	6.87
Specific conductivity (μS/cm)	21	34
Dissolved oxygen (mg/L)	8.02	8.89
Measured SWT (°C)	13.80	14.20
Average July SWT (°C)	17.33[a]	15.95[a]
Measured July AT (°C)	16.06[b]	16.35[c]

SWT = surface water temperature, AT = air temperature.
[a] Average measured SWT for July 2007.
[b] MJAT for July 2006 and July 2007.
[c] MJAT for July 2007.

evaluated. In addition, understanding the magnitude and range of past climate variability is vital for predicting future water availability and secondary ecological responses to climate change.

In this paper we develop a midge-based inference model for mean July air temperature (MJAT) specific to the Inter-Mountain West of the United States. In complex topographic environments, such as those that typify this region, it is often difficult to obtain the air temperature estimates that are required to constrain calibration sets (Porinchu et al., 2002, 2007a). We incorporated PRISM-derived air temperature values for MJAT to develop the midge-based inference model. This inference model was applied to the subfossil midges' remains extracted from two short cores recovered from sub-alpine lakes in Great Basin National Park (GBNP) to reconstruct the 20th and early 21st century air temperature regimes for this region. These reconstructions are compared to nearby climate division data to assess their quality. In addition, the midge stratigraphies are compared to previous chironomid studies from the Inter-Mountain West to determine whether a regionally synchronous response in faunal turnover is evident in sub-alpine lakes in this region.

2. Study area

Great Basin National Park is located in the Snake Range in the central Great Basin (Fig. 1). The Great Basin is an arid region distinguished by a basin and range structure with north–south trending valleys and mountains and interior drainage. This region, characterized by considerable climatic heterogeneity from east to west and north to south, receives most of its precipitation during the winter months as snow, with lesser amounts of precipitation associated with summer thunderstorms (Western Regional Climate Center, 2008). Elevation is the primary control on temperature and precipitation; however, precipitation is highly variable due to local and regional effects such as rain shadow, aspect, and monsoon status (Shin et al., 2006). High elevations (~3000 m) in GBNP are characterized by annual temperatures that range from 13.5 °C in summer to −7.0 °C in winter (Western Regional Climate Center, 2008). Lower elevations (~2070 m, Great Basin National Park Co-op Station) experience annual temperatures that range from 20.0 °C in summer to −1.0 °C in winter (Western Regional Climate Center, 2008).

The bedrock geology characterizing GBNP consists primarily of Cambrian quartzite, Paleozoic Miogeoclinal deposits, Jurassic granitic plutons, and Quaternary alluvial and glacial deposits present locally (Miller and Grier, 1995). The two study sites, Stella Lake and Baker Lake, are small (~3.0 ha), relatively shallow (1.60–2.50 m), circum-neutral (pH = ~7.0) and fed primarily from snowmelt with lesser contributions from groundwater. Selected limnological measurements for both lakes are available in Table 1. Stella Lake, situated at 3150 m asl, is underlain by Cambrian quartzite with late Quaternary glacial till present at the surface (Whitebread, 1969). Baker Lake is located at 3194 m asl beneath a steep, east-facing headwall. The Baker Lake catchment is dominated by Cambrian quartzite, with a small outcrop of Jurassic age quartz monzonite present (Miller and Grier, 1995). The surface geology surrounding Baker Lake consists of late Quaternary alluvium and glacial deposits (Whitebread, 1969). The composition of the vegetation

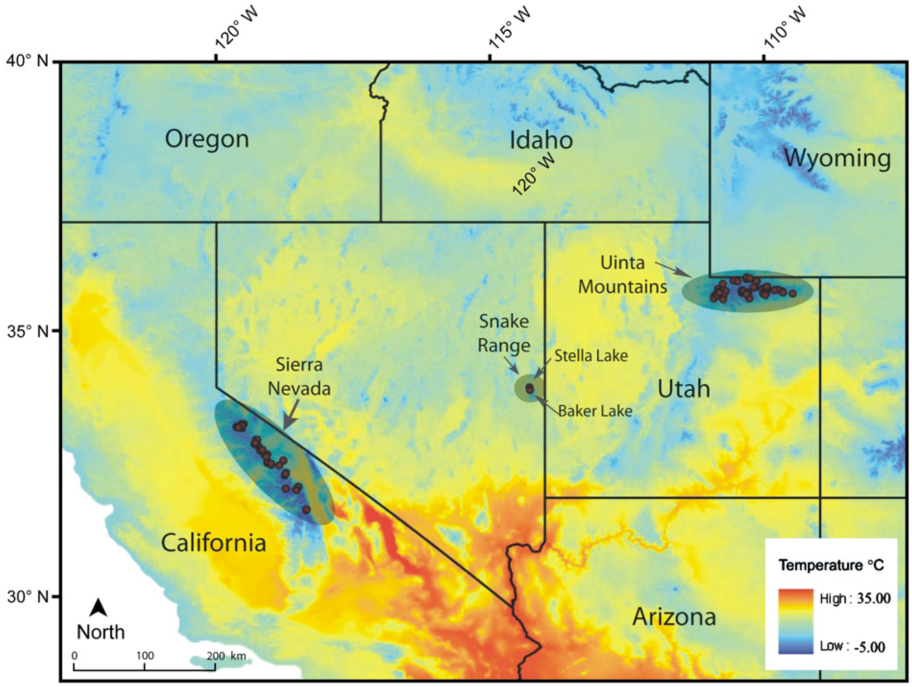

Fig. 2. Distribution of Inter-Mountain West training set lakes (Porinchu et al., 2007a) and digital output of the PRISM data for mean July air temperature (MJAT).

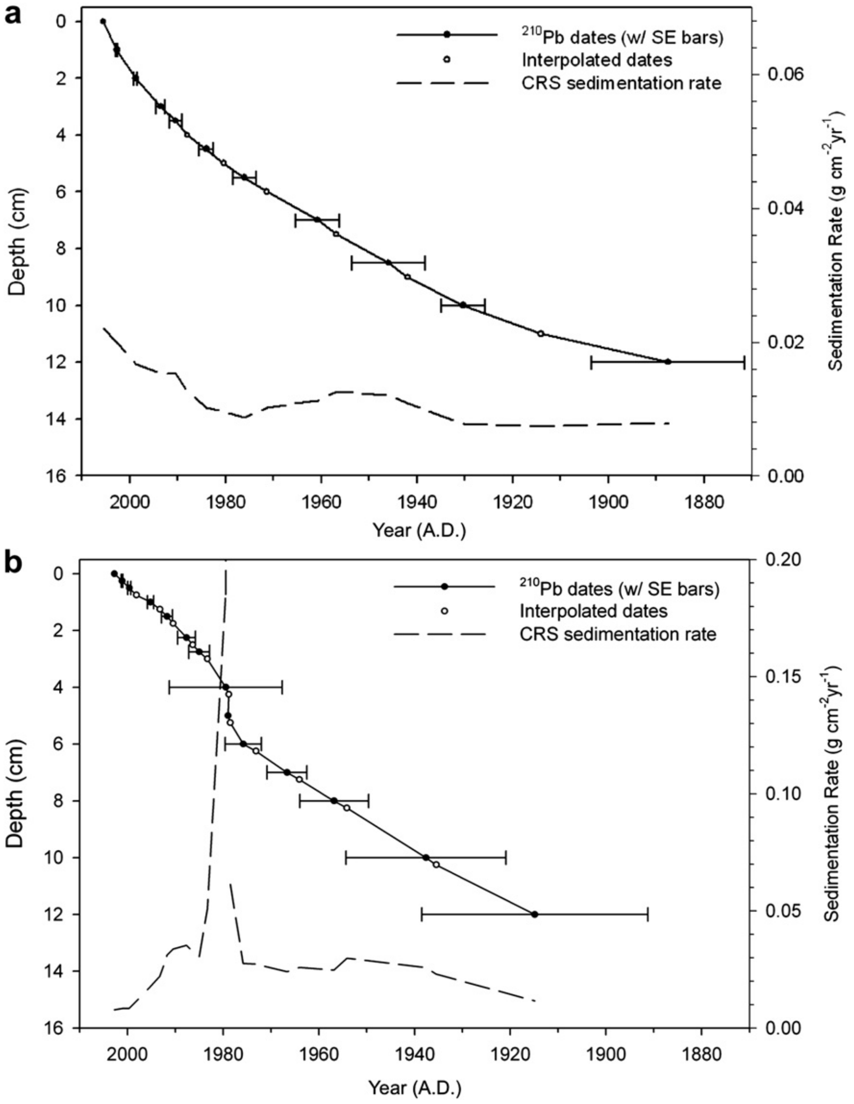

Fig. 3. ^{210}Pb chronologies for (a) Stella Lake and (b) Baker Lake, utilizing the constant rate of supply model (CRS) and sedimentation rates. SE = standard error.

communities in the vicinity of the study sites is a function of steep climate gradients (Eaton, 1982). High elevations (>2400 m) are dominated by *Picea engelmannii* (Engelmann spruce), *Pinus flexilis* (limber pine) and *Picea longaeva* (bristlecone pine) up to treeline, with alpine tundra present on isolated mountain summits, such as Wheeler Peak, Mount Washington, and Jefferson Davis Peak.

3. Methods

Sediment cores were recovered from Baker Lake and Stella Lake in August 2007 and August 2005, respectively, from the approximate center of each lake using a mini-Glew sediment corer (Glew, 1991). The sediment–water interface appeared to be undisturbed during sediment recovery, suggesting the flocculent uppermost sediment was obtained. The sediment cores measured 18.50 cm for Stella Lake and 12.75 cm for Baker Lake. The Stella Lake core was sectioned in the field at 0.50 cm intervals; the Baker Lake core was sectioned at 0.25 cm intervals. The sediment was stored in Whirl-paks and kept cool and in the dark during transport to the lab at The Ohio State University.

Measurement of limnological variables, such as surface water temperature, dissolved oxygen, salinity, specific conductivity and conductivity were made at the time of sediment collection using a YSI 556 multi-meter (Table 1). Secchi depth, max depth and temperature profiles (YSI) were also recorded at this time. In addition, detailed temperature profiles were recorded using micro-*T* temperature loggers (Nexsens Incorporated). Average July surface water temperatures for Stella and Baker lakes were based on the average value of measurements taken every 3 h during July 2007. The air temperature for each site was recorded using humidity/temperature USB data loggers (Lascar Electronics). The Lascar data loggers were housed in a temperature shroud, to shield them from direct sunlight, and positioned ~1.5 m above the ground. Measured July air temperatures were based on the average value of measurements taken every hour during July 2006 and July 2007 for Stella Lake and July 2007 for Baker Lake. The MJAT values used in calibrating the midge-based inference model were obtained from the PRISM climate data set (PRISM Group, 2007). The PRISM model provides climatologies that are useful in complex, mountainous terrain where there is a paucity of high-elevation meteorological stations and where simple lapse rate approximations would not be sufficient to capture real-world conditions (Daly et al., 2002) (Fig. 2).

To develop chronological control, 12 stratigraphic samples from each lake were analyzed for ^{210}Pb content. A 0.50–1.0 cm sampling

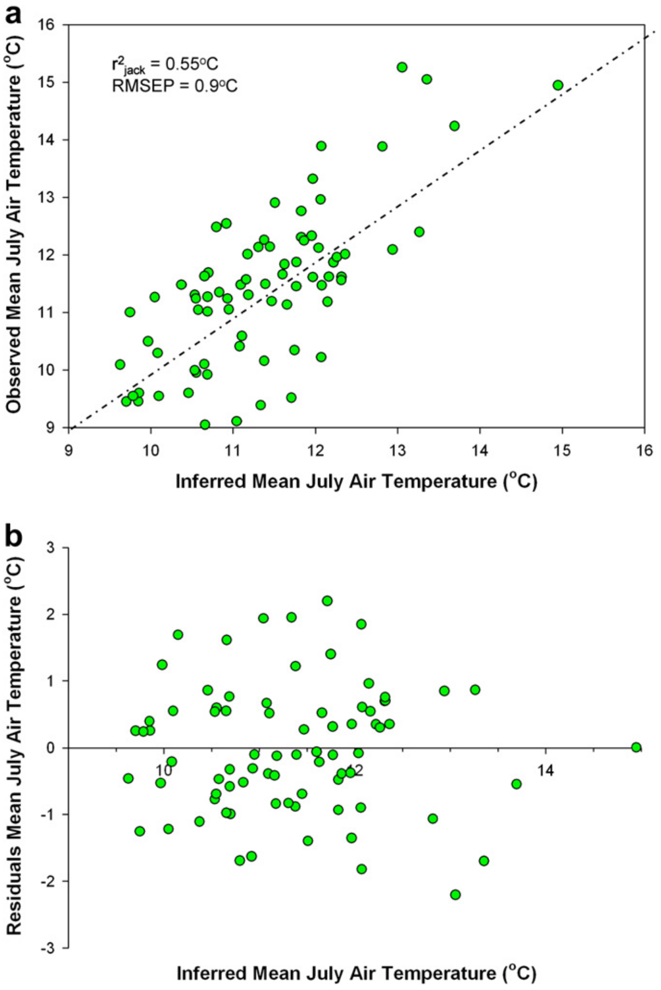

Fig. 4. (a, b) Relationship between inferred (jack-knifed) and (a) mean July air temperature (MJAT) obtained from PRISM and (b) residuals (inferred-observed) for MJAT based on two-component weighted averaging-partial least squares inference model.

Table 2
Values for non-rare taxa (i.e. taxa present in ≥5% of training set lakes) for: taxon occurrence (percent of lakes in which taxon was present), the minimum MJAT taxon was associated with (*T*-Min), maximum MJAT taxon was associated with (*T*-Max) and the beta coefficient values based on square-root transformed data (WA-PLS Beta transformed) used in the two-component WA-PLS MJAT model.

Taxon name	No. lakes	Occurrence (%)	*T*-Min (°C)	*T*-Max (°C)	WA-PLS Beta
Corynoneura/*Thienemanniella*	36	46	8.5	15.3	14.8237
Cricotopus/*Orthocladius*	49	62	9.1	15.3	10.7832
Doithrix/*Pseudoorthocladius*	5	6	9.4	13.9	9.21301
Eukiefferiella/*Tvetenia*	22	28	9.6	15.3	13.0841
Hydrobaenus/*Oliveridia*	19	24	9.4	13.9	10.0608
Limnophyes/*Paralimnophyes*	11	14	9.6	13.9	10.3459
Nanocladius	8	10	11.5	13.3	11.6782
Parakiefferiella bathophila	17	22	11.2	13.3	16.8058
Allopsectrocladius/ *Mesopsectrocladius*	20	25	9.1	13.9	17.9691
Psectrocladius (*Monopsectrocladius*)	14	18	9.4	15.3	14.8796
Psectrocladius semicirculatus/ *sordidellus*	72	91	8.5	13.9	12.9568
Psectrocladius Walker type	10	13	10.2	15.3	16.9421
Rheocricotopus	14	18	8.7	15.3	14.5054
Synorthocladius	29	37	8.5	13.3	5.64382
Zalutschia	49	62	8.5	13.9	12.8158
Heterotrissocladius	52	66	8.5	15.3	9.1277
Apedilum	5	6	11.1	15.0	15.4806
Chironomus	67	85	8.5	13.3	10.4668
Cladopelma	28	35	8.5	15.3	13.3379
Dicrotendipes	52	66	8.5	15.3	10.9847
Glyptotendipes	5	6	8.7	15.3	−0.332498
Microtendipes	49	62	8.5	15.0	10.6707
Pagastiella	14	18	11.3	15.0	20.5953
Phaenopsectra	8	10	10.3	15.0	20.58
Polypedilum	25	32	10.2	15.3	19.6121
Sergentia	21	27	9.0	15.3	6.34101
Stempellina	4	5	9.6	14.2	6.4333
Stictochironomus	4	5	10.2	14.9	19.5723
Cladotanytarsus	26	33	8.5	14.2	6.3595
Corynocera near *ambigua*	15	19	8.5	15.0	9.35219
Corynocera oliveri type	30	38	9.5	15.0	9.30729
Micropsectra	40	51	8.5	15.0	12.7144
Tanytarsus (spp. *A*/*C*)	9	11	11.1	15.3	19.9012
Tanytarsus type *A*	8	10	8.5	11.7	1.78189
Tanytarsus type *C*	18	23	10.2	15.0	12.1652
Tanytarsus type *D*	5	6	10.0	15.0	25.766
Tanytarsus type *E*	6	8	10.0	15.0	8.1868
Tanytarsus type *G*	24	30	8.5	13.0	6.27123
Tanytarsus type *H*	24	30	8.5	13.0	11.3491
Tanytarsus	78	99	8.5	15.3	11.455
Paratanytarsus	42	53	8.5	15.3	9.93223
Procladius	61	77	8.5	14.2	10.8586
Pentaneurini (other)	65	82	8.5	15.0	11.7294

interval was used to constrain the chronologies for the upper portion of the cores, and a 0.50–1.5 cm sampling interval was used to constrain the lower portion of the cores. Ages and sedimentation rates (g cm^{-2} yr^{-1}) were calculated using the constant rate of supply model (CRS), which is most robust in situations where the sediment accumulation rate changes through the core (Fig. 3a and b). A large cobble in the Baker Lake sediment core between 4.0 and 5.0 cm may have influenced the determination of the amount of unsupported ^{210}Pb present in this interval and likely accounts for the existence of a slight reversal in the Baker Lake chronology. The ^{210}Pb analysis was carried out by MyCore Scientific Incorporated (Dunrobin, Ontario, Canada).

Chironomid analysis follows Walker (2001). Subfossil midge remains were analyzed at 0.50 cm resolution, with a minimum of 50 head capsules analyzed at each interval (Quinlan and Smol, 2001). Identifications were based on Wiederholm (1983), Brooks et al. (2007), and an extensive reference collection of subfossil midge remains housed at The Ohio State University. The amount of sediment processed in order to yield a sufficient number of head capsules varied between 0.50 and 2.0 mL. The number of head capsules enumerated from Stella Lake and Baker Lake varied between 40 and 190 and 25 and 185 per ml, respectively.

The chironomid-based inference model for MJAT was developed for the Inter-Mountain West (IMW) using a weighted averaging-partial least squares (WA-PLS) approach (Birks, 1995). Training set taxonomy and the details describing the merging of the Sierra Nevada and Uinta Mountains calibration are available in Porinchu et al. (2007a). A two-component WA-PLS model provides the most robust performance statistics for MJAT, with an $r^2_{\text{jack}} = 0.55$, RMSEP = 0.9 °C, a maximum bias of 1.66 °C and no trend apparent in the residuals (Fig. 4a and b). The beta coefficients used in the two-component WA-PLS inference model are presented in Table 2.

Application of any transfer function to down-core assemblages will provide inferred values for the environmental variable of interest. The reliability of a quantitative paleoenvironmental reconstruction can be evaluated by determining for each subfossil assemblage the total percentage of taxa present down-core that do not appear in the modern calibration data set. According to Birks (1998), reconstructions that are based on subfossil assemblages that have >95% of the subfossil taxa present in the calibration set are very reliable. There were 17 chironomid taxa present in Stella Lake and 12 taxa present in Baker Lake; all subfossil taxa present in

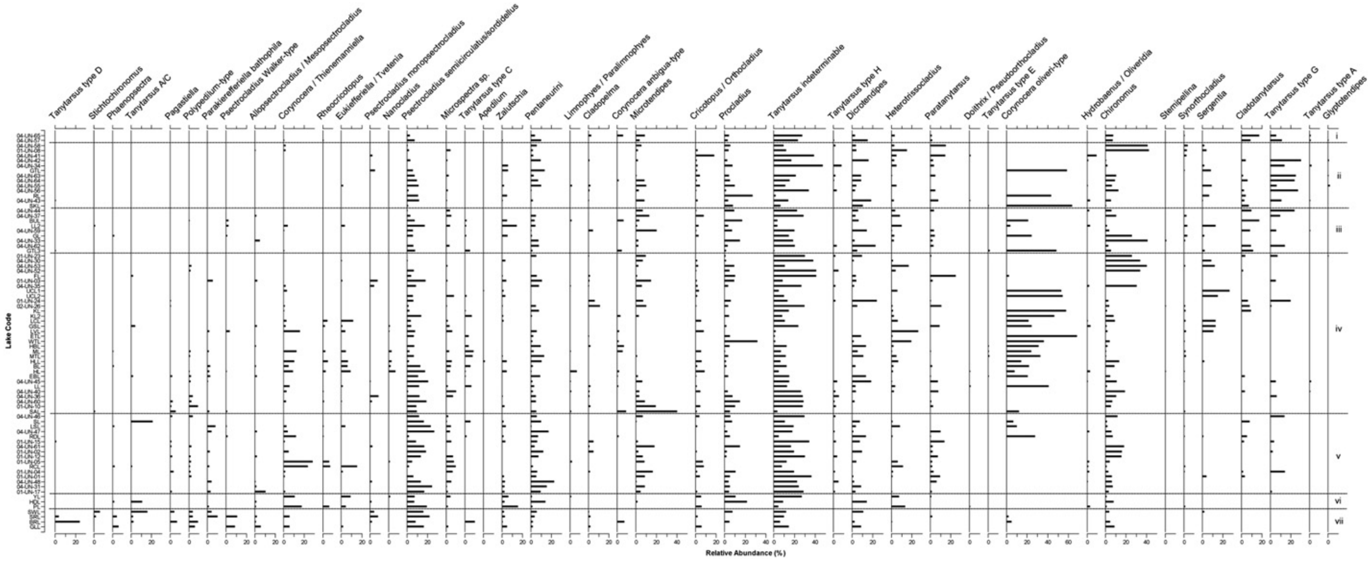

Fig. 5. Distribution along a mean July air temperature (MJAT) gradient of non-rare taxa (i.e. taxa present in >5% of training set lakes) found in the 79-lake Inter-Mountain West training set with the coldest lakes found at the top of the diagram. Categories of MJAT indicated by roman numerals (i = <9 °C; ii = 9 < 10 °C; iii = 10 < 11 °C; iv = 11 < 12 °C; v = 12 < 13 °C; vi = 13 < 14 °C; vii = ≥14 °C). Lake codes can be found in Porinchu et al. (2002, 2007a).

the short cores were present in the Inter-Mountain West training set. Another method of evaluating the reliability of inference model estimates involves determining the proportion of rare taxa present in the down-core samples (Birks, 1998). A taxon is classified as rare if it has an effective number of occurrences or Hill's N2 < 5 (Hill, 1973) in the calibration set. Taxa with Hill's N2 values > 5 in a training set can be considered well represented and will likely provide reliable estimates of temperature optima (Brooks and Birks, 2001). The taxa present in Stella Lake are well represented in the IMW calibration set with Hill's N2 diversity index values ranging between 4.7 and 69. With the exception of *Tanytarsus* type *B*, the taxa present in Baker Lake are well represented in the training set with Hill's N2 diversity index values ranging between 17.6 and 69, respectively. *Tanytarsus* type *B* is not well represented in the IMW training set (Hill's N2 = 1); *Tanytarsus* type *B* is present in eight down-core samples with a mean relative abundance of 8.3%. The program C2 (Juggins, 2003) was used to plot the chironomid percentage diagram, develop the WA-PLS inference models and estimate sample-specific error.

The subfossil assemblages present in Stella Lake and Baker Lake were plotted passively with the IMW training set lakes using correspondence analysis (CA). Correspondence analysis is a form of indirect gradient analysis that can be used to determine if down-core core assemblages are well represented in the IMW training set. De-trended correspondence analysis (DCA) of the assemblage data was undertaken to assess the correspondence between compositional turnover and the midge-based temperature reconstructions for Stella and Baker lakes. The CA and DCA were based on square-root transformed percentages of all midge taxa present in each sample in order to maximize the signal-to-noise ratio and stabilize variances (Prentice, 1980) and were implemented using CANOCO version 4.0 (ter Braak and Smilauer, 2002).

4. Results

4.1. Midge distribution – calibration set

Porinchu et al. (2007a) described the modern distribution of subfossil midges in the Inter-Mountain West in relation to summer surface water temperature (SSWT). The relationship between the distribution of midges in the Great Basin and MJAT is illustrated in Fig. 5. There are a number of taxa that are most abundant and typically restricted to the coldest lakes in the training set (MJAT optima indicated in parentheses) such as *Cladotanytarsus* (10.5 °C), *Sergentia* (10.8 °C), *Synorthocladius* (10.9 °C) and *Corynocera oliveri* (11.2 °C); whereas, taxa such as *Corynoneura/Thienemanniella* (12.0 °C), *Pagastiella* (12.5 °C), *Parakiefferiella bathophila*-type (12.5 °C) and *Polypedilum* (12.6 °C), and are most common and abundant in calibration set lakes that are characterized by relatively high MJAT. There are a number of taxa that have eurythermic distributions, e.g. *Procladius*, Pentaneurini (other) and *Psectrocladius semicirculatus/sordillelus*-type.

4.2. Midge percentage diagrams

4.2.1. Stella Lake

A total of 17 midge taxa were identified in the Stella Lake core. The midge community present in Stella Lake in the early 20th century (AD 1900–1940) is dominated by *Tanytarsus* type *G* and *Tanytarsus* (indeterminable) and lesser amounts of *P. semicirculatus/sordidellus*, *Procladius*, *Paratanytarsus* and *Tanytarsus* type *A* (Fig. 6a). The presence of *Rheocricotopus* and *Psectrocladius septentrionalis* is restricted to this interval. The midge community during the mid-20th century (~AD 1940–1970) is characterized by abundant remains of *Tanytarsus* type *G, Tanytarsus* (indeterminable) and increasing amounts of *P. semicirculatus/sordidellus*. *Tanytarsus* type *H* and *Paratanytarsus* are present at a relatively low abundance (~5%), *Paratanytarsus* is nearly extirpated and *Tanytarsus* type *A* is extirpated. *Sergentia* appears for the only time at ~AD 1970. An increase in *P. semicirculatus/sordidellus* and *Tanytarsus* type *H* (*TAH*) characterizes Stella Lake during the late-20th century (AD 1970 – present). *Cladotanytarsus mancus* group reappears in the core along with *Cricotopus/Orthocladius* and *Psectrocladius* Walker type which are found for the first time in the upper sediment. *Chironomus* and *Procladius* are present throughout the core at a constant relative abundance of ~5% and 10%, respectively. The modern midge community, represented by the uppermost sediment sample, is characterized by a large

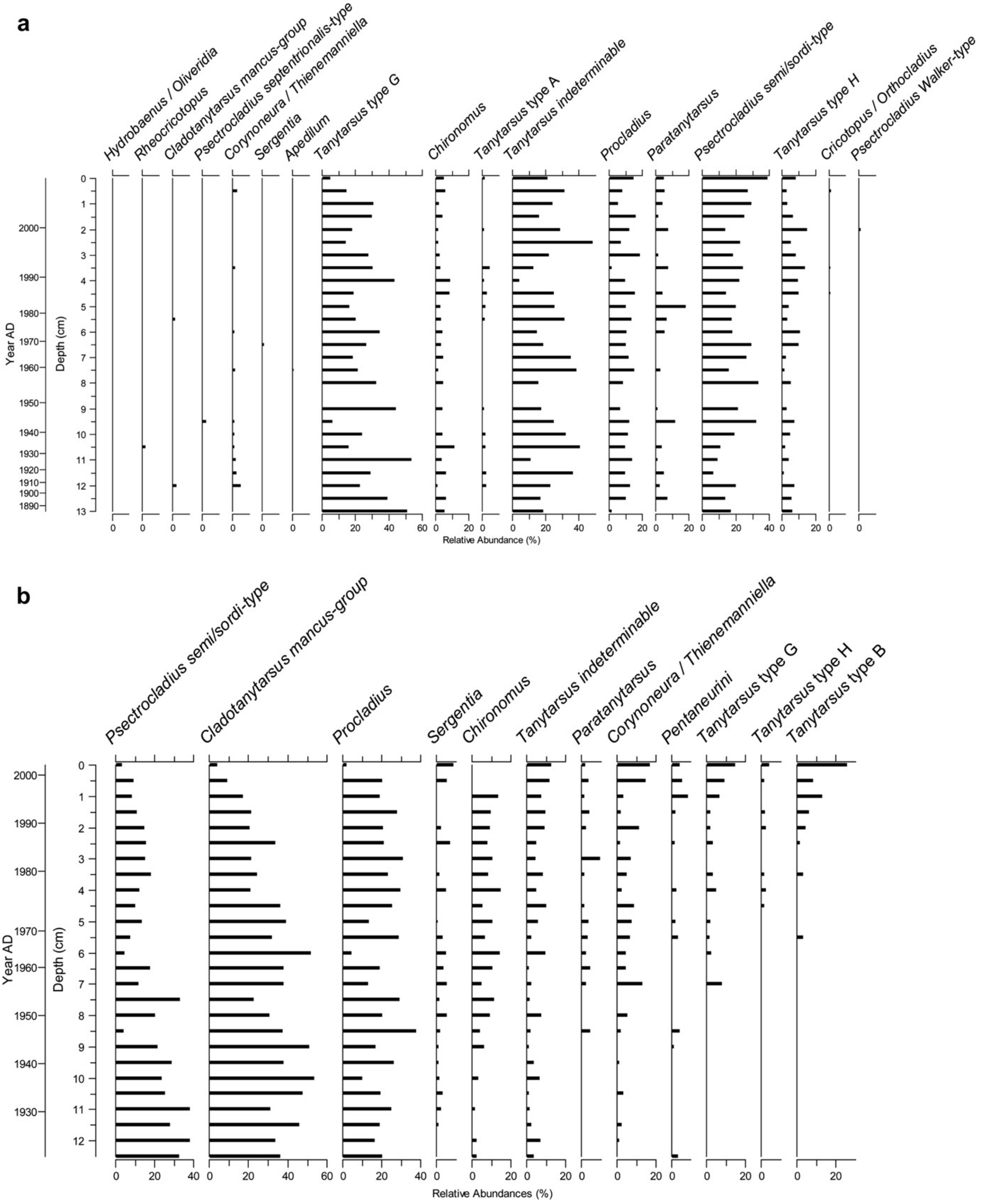

Fig. 6. Chironomid-percentage diagrams for (a) Stella Lake and (b) Baker Lake.

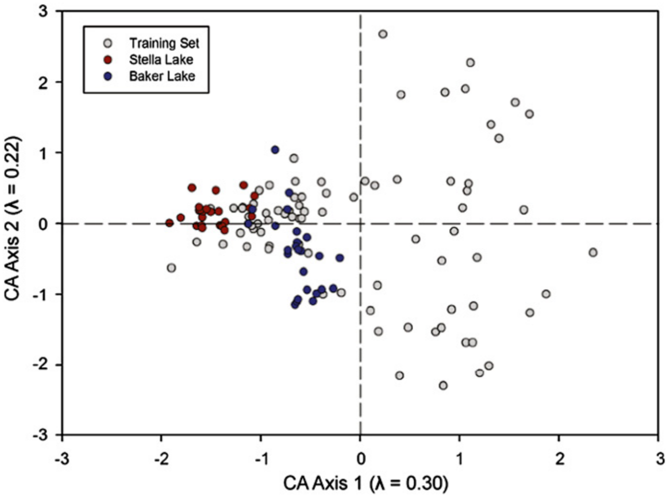

Fig. 7. Correspondence analysis (CA) passively plotting midge assemblages from Stella Lake and Baker Lake with chironomid assemblages present in the Inter-Mountain West midge training set.

compositional shift, with a reduction in the relative abundance of *Tanytarsus* type *G* and an increase in relative abundance of *P. semicirculatus/sordidellus* and *Tanytarsus* type *H.*

4.2.2. Baker Lake

The midge community in Baker Lake currently consists of a total of 11 taxa; however, the midge community was relatively depauperate in the early 20th century with only 8 taxa present until ∼AD 1940 (Fig. 6b). The early 20th century midge community consists primarily of *P. semicirculatus/sordidellus*, *Procladius* and *C. mancus* group. A decrease in the relative abundance of *P. semicirculatus/sordidellus* and an increase in the relative abundance of *Procladius*, *Chironomus* and *Corynoneura/Thienemanniella* characterize the midge community during the mid-20th century (AD 1940–1970). Taxa such as *Tanytarsus* type *G, Tanytarsus* type *H* and *Tanytarsus* type *B* appear for the first time in the core, albeit at very low levels (1–5%) during this interval. Pentaneurini, *Tanytarsus* type *G, Tanytarsus* type *H* and *Tanytarsus* type *B* increase in relative abundance during the late-20th century; whereas, *P. semicirculatus/sordidellus* and *C. mancus* group decrease. It is notable that *Procladius* is the only taxon in Baker Lake that is present at a relatively constant proportion throughout the core, until the most recently deposited sample. The abundance of *Chironomus*, relatively constant post-AD 1940, is approximately three times greater during this interval than its abundance between 1920 AD and 1940 AD. *C. mancus* group comprises approximately 35% of the midge community between 1920 AD and 1975 AD, after which time it decreases in relative abundance to approximately 20% until AD 2000 when its relative abundance decreases further to 5%. The abundance of *P. semicirculatus/sordidellus*, which decreases progressively through the core, is greatest during the early 20th century. The midge community experiences notable compositional change in the uppermost sediment, with increases in *Tanytarsus* type *G*, *Tanytarsus* type *B*, *Corynoneura/Thienemanniella*, and *Sergentia* and a decrease in *Chironomus*.

4.3. Ordination analyses

The subfossil midge assemblages from Baker and Stella Lakes were plotted passively against the assemblages in the IMW training set using correspondence analysis (CA) to determine if the Stella Lake and Baker Lake midge communities are represented in the regional training set (Fig. 7). The CA bi-plot indicates that the composition of the 20th century midge communities in Stella Lake and Baker Lake are located within the ordination space captured by the Inter-Mountain West calibration set. The eigenvalues for CA axes 1 and 2 are 0.31 and 0.22, respectively. Measured limnological and environmental data indicate that CA axis 1 appears to capture specific conductivity and depth gradients, whereas, CA axis 2 captures an MJAT gradient. De-trended correspondence analysis (DCA) reveals that relatively large sample-to-sample compositional turnover characterizes the Stella Lake midge community through the 20th century (Fig. 8). DCA axes 1 and 2 together capture ∼15% and 22% of the variance present in the Stella Lake and Baker Lake cores, respectively. DCA axis 1 indicates an abrupt change in faunal composition occurs at both lakes at ∼AD 1980. In Stella Lake, the change in faunal composition at AD 1980 is characterized by an increase in the relative abundance of *Tanytarsus* type *A*, *Chironomus*, *Paratanytarsus* and *Cricotopus/Orthocladius*. Compositional turnover during the 20th century in Baker Lake is uni-directional and of larger magnitude. Notable faunal turnover occurs post-AD 1980 in Baker Lake: *C. mancus* group and *Procladius* decrease; whereas, Pentaneurini, *Tanytarsus* type *G* and *Tanytarsus* type *B* increase in relative abundance. DCA axis 1 scores for both lakes do not track their respective chironomid-based MJAT inferences; however, there is a strong correspondence between MJAT estimates and DCA axis 2.

4.4. MJAT inference model: temperature estimates and deviations

Estimates of MJAT for the interval common to both cores, AD 1920–2005, are presented in Fig. 8. Sample-specific error estimates varies between 1.0 and 1.2 °C and 1.0 and 1.7 °C for Stella Lake and Baker Lake, respectively. Both lakes experienced large fluctuations in MJAT during the 20th century. Baker Lake is characterized by fluctuating MJAT between AD 1920 and AD 1940 and below average MJAT between AD 1940 and AD 1970. Stella Lake is characterized by highly fluctuating midge-inferred MJAT estimates between AD 1920 and AD 1970 and depressed temperature between ∼AD 1970 and AD 1980. MJAT begins to increase at Stella Lake and Baker Lake at ∼AD 1985 and AD 1990, respectively. Consistently above average temperature characterizes the late-20th century for both lakes. The rate of temperature change between AD 1920 and AD 2002 for Stella Lake and Baker Lake was 0.1 °C/100 years and 0.6 °C/100 years, respectively. The rate of warming increased dramatically for both lakes in the post-AD 1975 interval, with Baker Lake characterized by a rate of warming of 3.6 °C/100 years and Stella Lake by a rate of 3.7 °C/100 years.

A plot of the deviations of MJAT from the average chironomid-inferred MJAT for the interval for which well-constrained chronologies are available is presented in Fig. 9. In addition, deviations from the average July temperature for Nevada Climate Division #2 are also depicted (NCDC, 2007). Although the temporal resolution of the lake sediment samples (2–8 years/sample) is less than the annual resolution of the instrumental climate data, Fig. 9 suggests that similar trends characterize the records, especially during the late-20th century. Much of the mid-20th century in the region spanned by Nevada Climate Division #2 was characterized by near- or below average July temperature; a trend that is apparent in the reconstructed MJAT for Baker Lake. The late-20th century, specifically the post-AD 1990 interval, reveals a strong correspondence between the above average July temperatures recorded in Nevada Climate Division #2 and the above average MJAT estimates for Baker and Stella lakes.

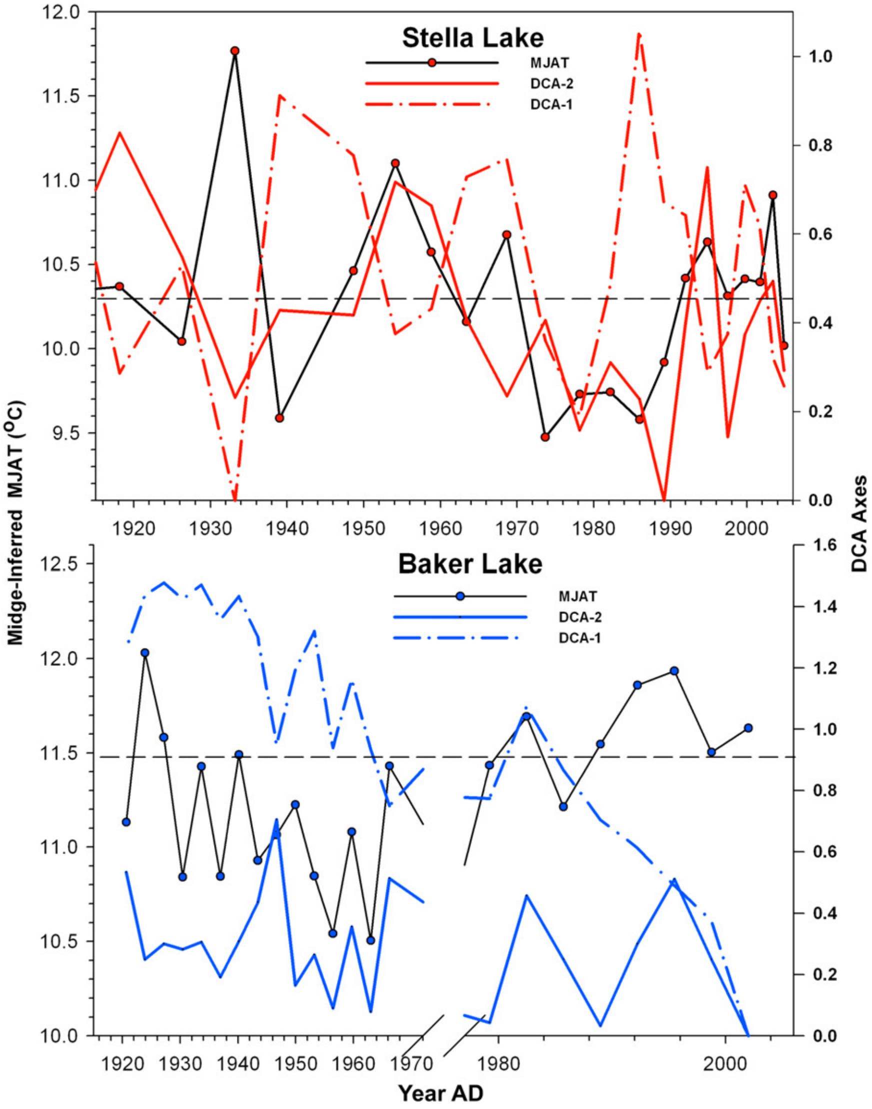

Fig. 8. Chironomid-based mean July air temperature (MJAT) reconstruction for Stella Lake and Baker Lake spanning the interval for which each lake has a well-constrained radiometric chronology. Points represent chironomid-based MJAT inferences. The dashed line is average chironomid-inferred MJAT for the well-constrained radiometric interval for each lake. The solid line and dash-dot line represent DCA axes 1 and 2 scores, respectively.

5. Discussion

Alpine and sub-alpine aquatic ecosystems are highly susceptible to the direct and indirect effects of climate change (Battarbee et al., 2002; Bradley et al., 2004; Parker et al., 2008). The remoteness of many high-elevation lakes in the Inter-Mountain West make these lakes ideal candidates for studying the potential of effects of climate forcing (Wolfe et al., 2003). Studies have documented anthropogenic influence, via nitrogen deposition or climate change, on high-elevation aquatic ecosystems in western North America (Wolfe et al., 2003; Nydick et al., 2004; Karst-Riddoch et al., 2005; Porinchu et al., 2007b). The duration and thickness of ice cover, along with the timing of ice-melt directly affect the physical and chemical characteristics and ecology of high-elevation lakes (Melack et al., 1997; Karst-Riddoch et al., 2005). For example, longer ice-free seasons resulting from the later onset and earlier ice-off will lead to stronger or longer thermal stratification and enhanced or prolonged nutrient suspension. This in turn may increase lake productivity and potentially facilitate the invasion/introduction of non-native species, which in turn will impact biodiversity and aquatic ecosystem functioning (Saros et al., 2003; Holzapfel and Vinebrooke, 2005).

Paleolimnological reconstructions of past climate require a detailed understanding of the relationship and linkages that exist between the proxy of interest and climate forcing (Birks, 1998). A multitude of forcing factors and their potential complementary effects on aquatic ecosystem composition, structure and function greatly increase the complexity of interpreting lacustrine records. For example, aquatic community composition and structure are influenced by: abiotic processes, e.g. water chemistry, lake depth and temperature; and biotic processes, e.g. trophic interactions and competition. The relative role that these processes play varies spatially and temporally, with the effects of climate and environmental change becoming increasingly important over longer timescales (Anderson et al., 2008). It is critical to establish whether the (paleo)-ecological trajectory of an aquatic community at a specific site is a direct response to climate forcing or a response to other factors such as vegetation development or changing hydrologic regimes. For example, recent work in the Canadian Arctic suggests that the late-20th century is characterized not only by

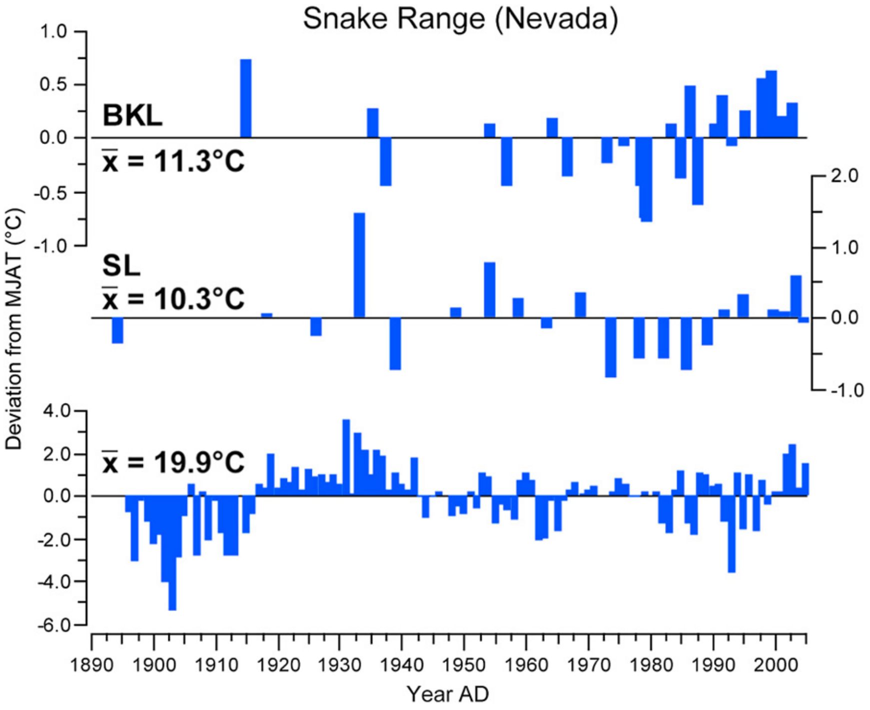

Fig. 9. Deviations of the chironomid-based mean July air temperature (MJAT) from the average MJAT for the well-constrained radiometric interval for (a) Baker Lake and (b) Stella Lake. (c) Deviations of air temperature from long-term average air temperature over the period 1895–2005 AD for Climate Division #2, Nevada (Western Regional Climate Center, 2008).

rapid turnover in diatom flora, but that stratification, likely resulting from a lengthening of the growing season and increased summer temperatures, may be altering diatom community structure (Ruhland et al., 2008).

The strengthening of thermal stratification may explain the concomitant increase in cold stenothermic and thermophilous taxa that occurs post-AD 1995 at Baker Lake. Repeat measurement of August water temperature between 2005 and 2007 at Baker Lake, a well-sheltered lake, indicates that it is currently stratified (Fig. 10). The upper sediment is characterized by an increase in *Sergentia* and *Corynoneura*/*Thienemanniella*. Sergentia is typically associated with cold, oligotrophic arctic lakes (Walker et al., 1997; Francis et al., 2006) or the bottom waters of deep, temperate lakes (Porinchu et al., 2002, 2007b). *Sergentia* has among the lowest MJAT optima in the Inter-Mountain West calibration set; whereas, *Corynoneura*/*Thienemanniella*, is a thermophilous taxon characterized by a relatively high MJAT optima (12.0 °C). Porinchu et al. (2009) identified a similar pattern, characterized by the concomitant increase in cold stenothermic and thermophilous taxa (Micropsectra and Corynoneura, respectively) in the surface sediment of a low arctic lake.

A previous study identified notable compositional turnover during the late-20th century in sub-alpine lakes in the western Great Basin (Porinchu et al., 2007b). The Baker Lake midge stratigraphy is characterized by the local extirpation of *Chironomus*. *Chironomus*, also known as the 'blood-worm' due to the presence of hemaglobin, is considered an oxy-regulator (Brodersen et al., 2008). Oxy-regulators can maintain near constant oxygen consumption in oxygen-poor conditions and therefore can tolerate low oxygen concentrations, hypoxia, and even anoxia for periods of time (Brodersen and Quinlan, 2006; Brooks et al., 2007). Oxygen availability directly affects benthic midge larvae (Heinis and Davids, 1993) by modulating respiration rates (Brodersen et al., 2004, 2008) and can thereby influence their distribution (Jonasson, 1984). Kling et al. (2003) suggest that the regional manifestation of global warming in temperate environments will likely include enhanced stratification resulting in increased hypolimnetic oxygen depletion in aquatic environments. The decrease in *Chironomus* characterizing recently deposited sediment (late-20th and early 21st centuries) in sub-alpine lakes in the eastern Sierra Nevada (Porinchu et al. 2007b) and in the Uinta Mountains (Porinchu, unpublished data) may be further indication that lake water stratification is beginning to affect chironomid community composition in the Great Basin. Continued monitoring of sub-alpine and alpine lakes in the western United States is required to more fully substantiate whether altered midge community composition is a direct response to climate change, i.e. increasing MJAT, or an indirect response to climate change, i.e. strengthened lake water stratification or lengthening of the ice-free season.

The utility of subfossil midge analysis to reconstruct 20th century climate variability in sub-alpine lakes in the western Great Basin has been previously demonstrated (Porinchu et al., 2007b). The influence of land-use change or nutrient loading via atmospheric deposition of nitrogen as potential drivers of the faunal turnover identified in these chironomid stratigraphies could not be ruled out (Porinchu et al., 2007b). The central Great Basin, an expansive area with limited ranching and agriculture as has experienced negligible land-use change in the late-20th century, an interval of dramatic compositional turnover in the midge community, as evidenced in Stella and Baker Lakes. This study identifies the occurrence of regionally synchronous changes in site-specific midge community composition during the late-20th century, further supporting climate forcing as the driver responsible for these changes. A strong correspondence exists between DCA axis 2 and the midge-based MJAT estimates; however, it is important to acknowledge that additional site-specific factors such as hydrologic balance, lake productivity and water chemistry can

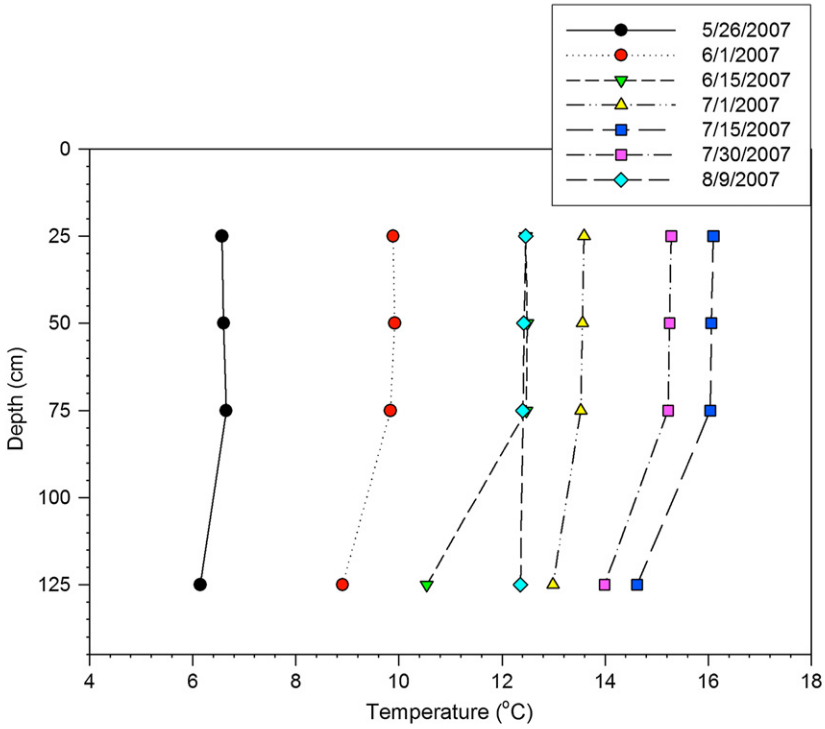

Fig. 10. Temperature profile for Baker Lake measured using micro-*T* temperature loggers. Average July surface water temperatures for Stella and Baker Lakes were based on the average value of measurements taken every 3 h during the month of July (see text for further detail).

influence midge community composition (likely captured by DCA axis 1).

The faunal turnover that characterizes midge communities in sub-alpine lakes in the western and central Great Basin further supports exploiting lake sediment archives in GBNP to elucidate changes in climatic conditions during the 20th and 21st centuries. Extending these records further into the past, i.e. the middle to early Holocene, will enable reconstruction of Great Basin paleoclimate over a longer timescale, put contemporaneous changes into context and increase our understanding of the linkage between these localized changes and regional climate dynamics.

6. Conclusions

Chironomid profiles spanning much of the 20th century were developed for two sub-alpine lakes located in Great Basin National Park, NV. Notable compositional turnover occurs in Stella and Baker lakes post-AD 1980. Stella Lake is characterized by increases in warm water taxa such as *P. semicirculatus/sordidellus*; whereas, the midge community in Baker Lake experiences a simultaneous increase in thermophilous littoral and profundal taxa, *Corynoneura/Thienemanniella* and *Sergentia*, respectively. The decline in *Chironomus*, which characterizes the most recently deposited sediment in these lakes appears to be regionally synchronous, suggests that lake water stratification may be affecting midge community composition in the Great Basin. A robust chironomid-based inference model for MJAT, developed for the Inter-Mountain West of the United States, applied to the chironomid stratigraphies from Great Basin National Park, provided high-resolution reconstructions of the 20th climate regime for the region. Correspondence between the midge-based inferences and instrumental records, especially during the late-20th century, substantiates the use of subfossil midge analysis for Holocene paleotemperatures reconstructions for the Inter-Mountain West of the United States.

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