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Six millennia of summer temperature variation based on midge analysis of lake sediments from Alaska

Benjamin F. Clegg[a], Gina H. Clarke[b,c,1], Melissa L. Chipman[b,c], Michael Chou[a], Ian R. Walker[d], Willy Tinner[e], Feng Sheng Hu[a,b,c,*]

[a] Program in Ecology, Evolution, and Conservation Biology, University of Illinois, Urbana, IL 61801, USA
[b] Department of Plant Biology, University of Illinois, Urbana, IL 61801, USA
[c] Department of Geology, University of Illinois, Urbana, IL 61801, USA
[d] Biology and Earth and Environmental Sciences, University of British Columbia Okanagan, Kelowna, BC V1V 1V7, Canada
[e] Oeschger Centre for Climate Change Research and Institute of Plant Sciences, University of Bern, Altenbergrain 21, CH-3013 Bern, Switzerland

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ABSTRACT

Despite their importance for evaluating anthropogenic climatic change, quantitative temperature reconstructions of the Holocene remain scarce from northern high-latitude regions. We conducted high-resolution midge analysis on the sediments of the past 6000 years from a lake in south-central Alaska. Results were used to estimate mean July air temperature (T_{July}) variations on the basis of a midge temperature transfer function. The T_{July} estimates from the near-surface samples are broadly consistent with instrumental and treering-based temperature data. Together with previous studies, these results suggest that midge assemblages are more sensitive to small shifts in summer temperature (~0.5 °C) than indicated by the typical error range of midge temperature transfer functions (~1.5 °C). A piecewise linear regression analysis identifies a significant change point at ca 4000 years before present (cal BP) in our T_{July} record, with a decreasing trend after this point. Episodic T_{July} peaks (~14.5 °C) between 5500 and 4200 cal BP and the subsequent climatic cooling may have resulted from decreasing summer insolation associated with the precessional cycle. Centennial-scale climatic cooling of up to 1 °C occurred around 4000, 3300, 1800–1300, 600, and 250 cal BP. These cooling events were more pronounced and lasted longer during the last two millennia than between 2000 and 4000 cal BP. Some of these events have counterparts in climatic records from elsewhere in Alaska and other regions of the Northern Hemisphere, including several roughly synchronous with known grand minima in solar irradiance. Over the past 2000 years, our T_{July} record displays patterns similar to those inferred from a wide variety of temperature proxy indicators at other sites in Alaska, including fluctuations coeval with the Little Ice Age, the Medieval Climate Anomaly, and the First Millennial Cooling (centered around 1400 cal BP). To our knowledge, this study offers the first high-resolution, quantitative record of summer temperature variation that spans longer than the past 2000 years from the high-latitude regions around the North Pacific.

1. Introduction

Evaluating anthropogenic effects on the Earth's climate system requires proxy records of natural climatic variation at decadal to millennial timescales. This rationale has motivated numerous paleoclimate studies and resulted in a proliferation of Holocene climate records, especially those focusing on the past two millennia. Among the most important results are the uniqueness of 20th-century warming and the spatially heterogeneous expressions of climate change. In Alaska, several decades of paleo-studies have amassed a large database of multi-proxy climate indicators that span the Holocene and beyond, including pollen, treering, sedimentological, and geochemical records (e.g., Anderson and Brubaker, 1994; Hu et al., 1998, 2003; Wiles et al., 1998, 2008; Abbott et al., 2000; Anderson et al., 2001; Brubaker et al., 2001; Tinner et al., 2008; McKay and Kaufman, 2009; Barclay et al., 2009; Clegg and Hu, 2010). These records offer insights into past

* Corresponding author. Department of Plant Biology, University of Illinois, Urbana, IL 61801, USA. Tel.: +1 217 244 2982; fax: +1 217 244 7246.
E-mail address: fshu@life.uiuc.edu (F.S. Hu).
[1] Present address: Environmental Change Research Centre, University College London, Pearson Building, Gower Street, London WC1E 6BT.

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changes in temperature, moisture, atmospheric circulation patterns, and ecosystem processes. However, the majority of these records provide qualitative inferences, and in many cases it is difficult or impossible to disentangle the controlling factors that led to fluctuations in various proxy indicators in lake sediments. These problems greatly diminish the value of these records to assess the relative importance of various climatic drivers and to provide baseline information for recent warming. Although several recent studies have attempted to quantify temperature fluctuations from lake-sediment analyses (Hu et al., 2001; Loso et al., 2006; McKay et al., 2008; Kurek et al., 2009; Kurek and Cwynar, 2009), quantitative summer temperature records remain scarce from Alaska.

Analysis of midge (chironomid, chaoborid, and ceratopogonid) assemblages has proven effective for reconstructing summer temperature (Battarbee et al., 2002). Midge larvae are highly sensitive to summer lake-water temperature, which reflects air temperature in lakes without strong thermal stratification, and fossil midge assemblages preserved in lake sediments have been applied to quantify temperature changes (e.g., Walker et al., 1991; Levesque et al., 1994; Brooks and Birks, 2001; Larocque and Bigler, 2004; Porinchu et al., 2009). Midge transfer functions of July temperature and other variables were recently developed for Alaska and adjacent regions (e.g., Walker et al., 2003; Barley, 2004; Barley et al., 2006) and used to elucidate millennial-scale climate variation during the late-Quaternary (Kurek et al., 2009). As with other midge-based temperature reconstructions, applications of this temperature transfer function may be hampered by the small range of Holocene variation relative to the statistical uncertainties of the transfer function. However, a number of studies from high-altitude and high-latitude lakes in various regions have demonstrated the reliability of midge assemblages for quantitative reconstruction of Holocene temperature changes (e.g., Seppä et al., 2002; Heiri et al., 2003; Larocque and Hall, 2003; Rosenberg et al., 2004; Chase et al., 2008).

We analyzed sediments of the past 6000 years from Moose Lake (61°22.45′N, 143°35.93′W, 437 m a.s.l.) in south-central Alaska for midge assemblages at decadal to centennial resolution. Here we report the results and use the assemblage data to derive mean July air temperature (T_{July}) estimates using the transfer function of Barley et al. (2006). The reliability of this approach at Moose Lake is evaluated by comparing midge-based T_{July} estimates with weather-station and treering-based temperature data from the same region (Davi et al., 2003). We then discuss temperature fluctuations at centennial and millennial timescales over the past six millennia and explore the factors causing these fluctuations.

2. Site description

Moose Lake is located in the Chitina River drainage of the Wrangell-St Elias National Park and Preserve in south-central Alaska, bordered to the north and south by the Wrangell and Chugach Mountains (Fig. 1). This oligotrophic lake is a topographically closed basin in a gently rolling topography. Its surface area and maximum depth are 21.5 ha and 4.5 m, respectively. In the summer of 2007, the conductivity and temperature of the surface water were 316.8 μS and 19.2 °C, respectively, and the lake was not thermally stratified. Today the lake is surrounded by boreal forest dominated by *Picea glauca* Moench, *Populus tremuloides* Michaux, and *Betula neoalaskana* Sargent, with patches of *Alnus viridis* ssp. *crispa* (Aiton) Turrill and *Salix* sp. L. thickets. *Picea mariana* (Mill.) B.S.P. stands occupy poorly drained soils to the west. At Gulkana, ~120 km NW of Moose Lake, mean annual and July air temperatures are −2.7 °C and 14.1 °C, respectively, and mean annual precipitation is 27.6 cm. Modern human influence in the watershed commenced with the AD 1907–1911 construction of the Copper River and Northwestern Railway, which passed within 10 m of the lake's shoreline. Pollen analysis at Moose Lake shows vegetational change accompanying the onset of local logging for the railway construction (Meier, 2003).

3. Materials and methods

We obtained two stratigraphically overlapping sediment cores using a Streif corer equipped with an electric hammer. In addition,

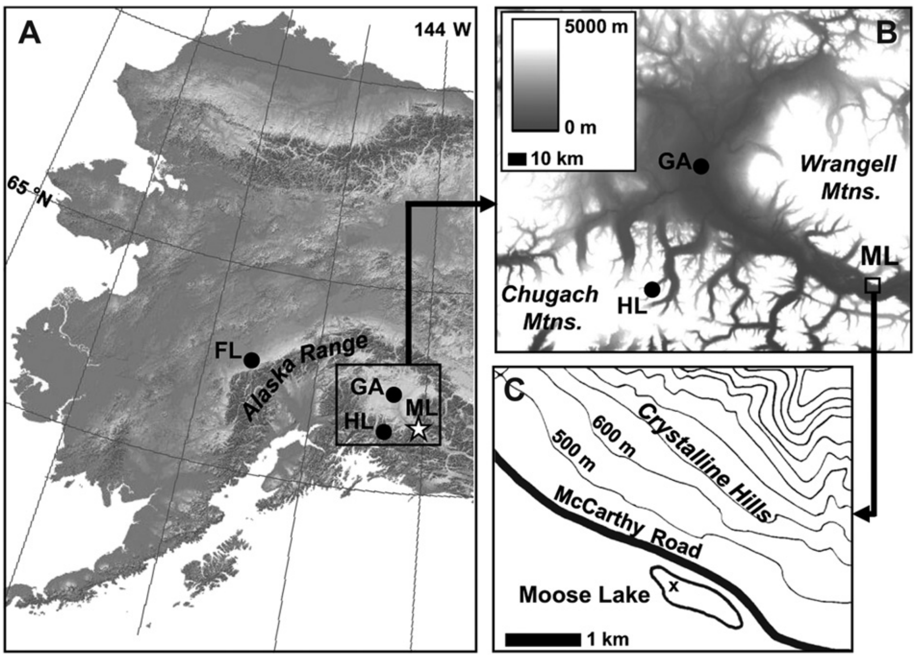

Fig. 1. (A) Locations of Moose Lake (ML) and other sites mentioned in the text (HL: Hallett Lake; FL: Farewell Lake; GA: Gulkana Airport weather station). (B) Topographic map of the Copper River Basin. (C) Moose Lake and surrounding area; X denotes coring location within lake.

we retrieved a short core containing the upper 53 cm of sediment and an intact sediment–water interface using a polycarbonate tube fitted with a piston. The cores were taken in the summer of AD 2000, and the core locations were about 1 m from one another in the deepest part of the lake. The long cores were correlated on the basis of numerous lithological markers to ensure that no stratigraphic gaps existed. After lithological description, one core was sectioned into contiguous 1 cm intervals and stored in scintillation vials at 4 °C. The short core was sampled at contiguous 1 cm intervals in the field, and correlated with the long core based on a pronounced magnetic-susceptibility peak associated with a silt band at 43 cm below the sediment–water interface. Subsamples from the same sediment sequence were used for the fire-history study reported in Lynch et al. (2004) and for the midge assemblage analysis in this study.

For chronological control, we used the ^{210}Pb ages for the uppermost 10 cm sediments and ten AMS (accelerator mass spectrometry) ^{14}C ages from the lower sediments (Table 1). The ^{14}C ages include six new samples in addition to the upper four samples of Lynch et al. (2004). The remaining three ^{14}C ages reported in Lynch et al. (2004) were not used in the present study because they came from the sediments older than 6000 cal BP with extremely rapid deposition rates. The materials for ^{14}C analysis are all plant macrofossils with the exception of one *Picea*-pollen extract (from 35 cm depth). The macrofossil at 78.5 cm was a node from a non-lignified plant stem and could have derived from either a terrestrial herbaceous plant or an aquatic macrophyte. The remaining ages were on terrestrial plant macrofossils. All ^{14}C ages were calibrated to years before AD 1950 (cal BP) in Oxcal 4.1 using the IntCal09 calibration curve (Reimer et al., 2009). An age-depth model was calculated from the ^{14}C and ^{210}Pb ages with a LOESS spline (span width = 6/16).

We conducted chironomid analysis on contiguous 1 cm intervals for the past 6000 years. Wet-sediment samples (2–3 cm^3 each) were prepared with a modified protocol of Walker et al. (1991). Treatment with HCl was omitted because no substantial amount of carbonate was present in the Moose Lake sediments. All head capsules of chironomids and ceratopogonids as well as *Chaoborus* mandibles in the residue were isolated under 50× magnification, dried onto standard microscope slides, and mounted using Entellan®. Identification of the remains proceeded under 400× magnification following Walker (1988, 2007), Wiederholm (1983), and Oliver and Roussel (1983). Taxonomic resolution was harmonized with Barley et al. (2006).

We estimated T_{July} from midge assemblages using the two-component weighted averaging partial least squares (WA-PLS) model of Barley et al. (2006) with a reported error envelope of 1.46 °C. The model training set includes surface sediment samples from sites spanning Alaska and neighboring regions (British Columbia, Yukon Territory, Northwest Territories). Temperature estimates were only obtained from samples with >50 midge head capsules each (Heiri and Lotter, 2001). Samples with a total count below 50 head capsules were either excluded ($n = 30$), or up to three adjacent samples were combined to achieve a minimum count of 50 ($n = 9$; equivalent to reduced sampling resolution). Modern analogue testing was performed by calculating the square-chord distance (Overpeck et al., 1985) between each downcore midge assemblage from Moose Lake and each of the assemblages in the training set of Barley et al. (2006). Samples outside the 75th and 95th percentiles of the training set square-chord distances were identified as poor and no analogues, respectively (Barley et al., 2006). Midge assemblages for each sample were passively loaded in a canonical correspondence analysis (CCA) of the training set to determine the dominant environmental drivers of variation. To help identify the break point between the multi-millennial trends apparent in our T_{July} record, we performed a change point analysis on the record using a two-line linear regression (Zar, 1999). The selected change point maximizes the adjusted R^2 of the two-line piecewise model (adjusted $R^2 = 0.41$) and exceeds the adjusted R^2 of the one-line model (adjusted $R^2 = 0.27$).

4. Results and discussion

4.1. Chronology

Activity of ^{210}Pb in near-surface sediment samples reaches the supported (background) level at 10 cm where an old-age-corrected age (Binford, 1990) of 64 cal BP is obtained (Lynch et al., 2004). The ^{14}C ages are generally in stratigraphic order (Table 1). However, the calibrated age of the pollen extract at 35 cm is ~425 years older than expected from linear interpolation of adjacent macrofossil ages and is excluded from the age model (Fig. 2B). Although some studies indicate no systematic bias in carbon isotopic fractionation for sporopollenin (Brown et al., 1992), the dominant chemical constituent of subfossil pollen, others have found similar discrepancies for ^{14}C ages on pollen extracts (Higuera et al., 2009). On the basis of the age model, our sampling resolution of 1 cm core interval is equivalent to 36.8 years on average for the past 6000 years. However, the actual temporal resolution of our T_{July} record is substantially lower because of the sediment intervals where <50 midge head capsules were found (Fig. 3). These intervals mostly occur before 4500 cal BP (Fig. 3) and generally correspond to silt layers in the core (Fig. 2A).

Table 1
AMS ^{14}C ages from the Moose Lake sediment core.

Lab ID	dated material	Depth [cm]	^{14}C age [years BP]	±error [years]	calibrated age [cal BP]	2σ error of cal age [years]
131,673[a]	charcoal	24–25	320	35	385	85
14,756[b]	lignified material	29–30	370	35	460	65
107,027[a,c]	pollen	34–36	1030	40	955	55
131,674[a]	wood	40–41	600	45	595	65
145,304[a]	needle	51–52	1575	35	1461	75
80,803[a]	wood	55–56	1730	40	1636	86
145,305[a]	epithelium	78–79	2970	50	3115	152
84,950[a]	needle	110–111	3485	40	3756	116
80,799[a]	wood	130–131	4005	45	4478	177
80,800[a]	wood	168–169	5250	40	6004	80

Ages with CAMS and POZ numbers were analyzed at the Lawrence Livermore National Laboratory's Center for Accelerator Mass Spectrometry, Livermore, CA, USA and the Poznan Radiocarbon Laboratory, Poznan, Poland, respectively.

[a] CAMS.
[b] POZ.
[c] Sample excluded from age model; see details in text.

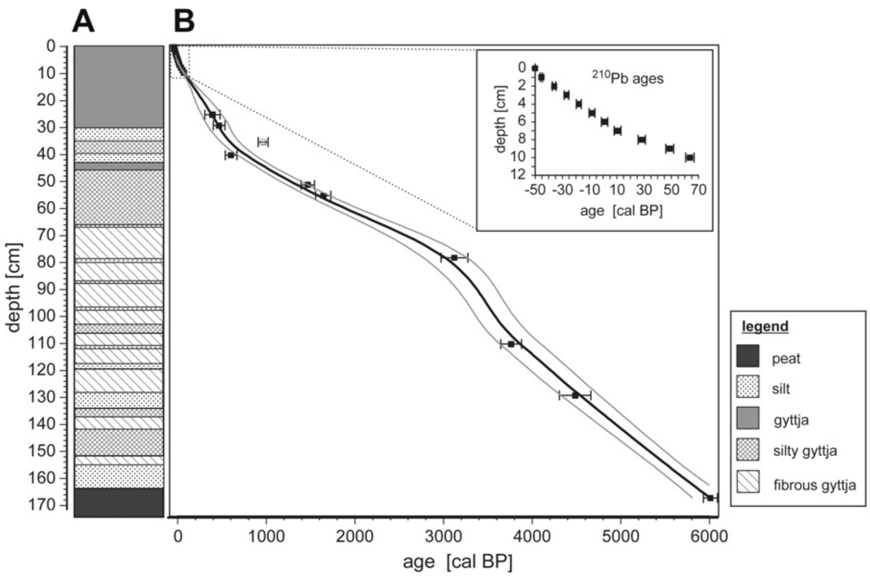

Fig. 2. (A) Lithology of the Moose Lake sediments. (B) Age-depth model based on ^{210}Pb ages of bulk sediments and calibrated ^{14}C ages; solid squares indicate ages on macrofossils, and empty square indicates age on spruce pollen extract (not included in age model). Inset shows detail of the upper 10 cm. Error bars represent 2-sigma ranges.

4.2. Evaluating midge assemblages as a proxy indicator of July temperature

The midge assemblages at Moose Lake are dominated by littoral taxa throughout the past 6000 years (Fig. 3C). *Microtendipes* Kieffer and 'Tanytarsina other' (mainly *Tanytarsus* v.d.Wulp), both common components of oxygenated, littoral settings, constitute ~40–80% of the total head capsule counts. Obligate profundal taxa of subarctic lakes are absent, and facultative profundal taxa rarely exceed 20% of the total count with *Chironomus* Meigen as the dominant type. Down-core assemblage changes are largely limited to variation in the relative abundance of various midge taxa, instead of complete replacement of taxa. Warm-indicator taxa of the tribe Chironomini (*Cryptotendipes* Lenz, *Endochironomus* Kieffer, *Polypedilum* Kieffer, and *Dicrotendipes* Kieffer) reach maximal abundances between 5500 and 3400 cal BP, whereas taxa with more moderate temperature optima (e.g., *Microtendipes* and *Cladotanytarsus* Kieffer) peak slightly later in the middle Holocene. Cool-indicator taxa, such as the subtribe Tanytarsina (represented by *Tanytarsus* and *Paratanytarsus* Thienemann&Bause), exhibit peak abundances both early in the record (6000–5500 cal BP) and after 3000 cal BP. The eurythermic taxon *Chironomus* peaks between 2000 and 400 cal BP.

The midge assemblages of >95% of our samples have good modern analogues (within the 75th percentile of the training set square-chord distances) (Fig. 3A). In addition, the strong correlation between our T_{July} and CCA axis1 sample scores ($r = -0.71$, $p < 0.001$, $n = 129$) suggests that July temperature is a dominant control of midge assemblages, although dissolved organic carbon and lake depth also load weakly onto CCA axis1 (Barley et al., 2006). These results suggest that our midge assemblage data have the potential to provide reliable T_{July} inferences. However, the T_{July} variation at Moose Lake does not exceed 2 °C over the past 6000 years. This range remains within the error envelope of the WA-PLS temperature inference model (±1.46 °C; Barley et al., 2006), similar to midge-based temperature records of the Holocene from other regions (e.g., Heiri et al., 2003). Caution is thus warranted when interpreting midge-based temperature records on Holocene timescales, especially if environmental variables other than summer temperature have varied within the lake and its watershed (Brooks, 2006).

To evaluate the performance of the midge T_{July} model of Barley et al. (2006) at Moose Lake, we compare our T_{July} inferences with instrumental and independent proxy temperature data. The youngest sample of the Moose Lake midge record (from 3.0 to 3.5 cm core depth; we did not have adequate amount of sediment from 0 to 3 cm for midge analysis) encompasses sediment deposition of AD 1968–1972. The inferred T_{July} from this sample (13.76 ± 1.43 °C) compares favorably with the mean of instrumental July temperatures of the same period (13.77 ± 1.13 °C, corrected for a dry adiabatic lapse rate of 9.80 °C per km) as recorded at a nearby weather station (Gulkana Airport). The relatively coarse resolution of the Moose Lake midge record, along with the brevity of weather-station records from our study region (~50 years), precludes a further assessment of our midge-based T_{July} estimates through comparison with instrumental climate data. However, the midge T_{July} estimates of the past 350 years (Fig. 4A) can be compared with treering temperature estimates of the same period from tree line sites in the Wrangell Mountains (Davi et al., 2003; Fig. 4B). In general, the midge temperature inferences parallel the treering temperature patterns. For example, the two records exhibit similar magnitudes of climatic warming after the Little Ice Age (LIA) and both capture low temperatures corresponding to the middle and late phases of the LIA, which also coincide with local advances in valley glaciers within the Wrangell Mountains (Wiles et al., 2004). However, the specific peaks and troughs do not always match between the two records, which is expected given the chronological uncertainties associated with our ^{210}Pb ages and with the age-depth model for samples older than 64 cal BP.

These results contribute to a growing body of evidence demonstrating the utility of midge assemblages for reconstruction of relatively small T_{July} variation on both historic and Holocene timescales (e.g., Heiri et al., 2003; Larocque and Hall, 2003). Together, these studies indicate greater sensitivity of midge assemblages to T_{July} variation than implied by reported error envelopes of midge temperature transfer functions. A plausible explanation is the greater temporal constancy of environmental factors, such as elevation, bathometry, bedrock type, and edaphic factors affecting lake chemistry, at an individual site where down-core midge analysis is performed for T_{July} reconstruction. In

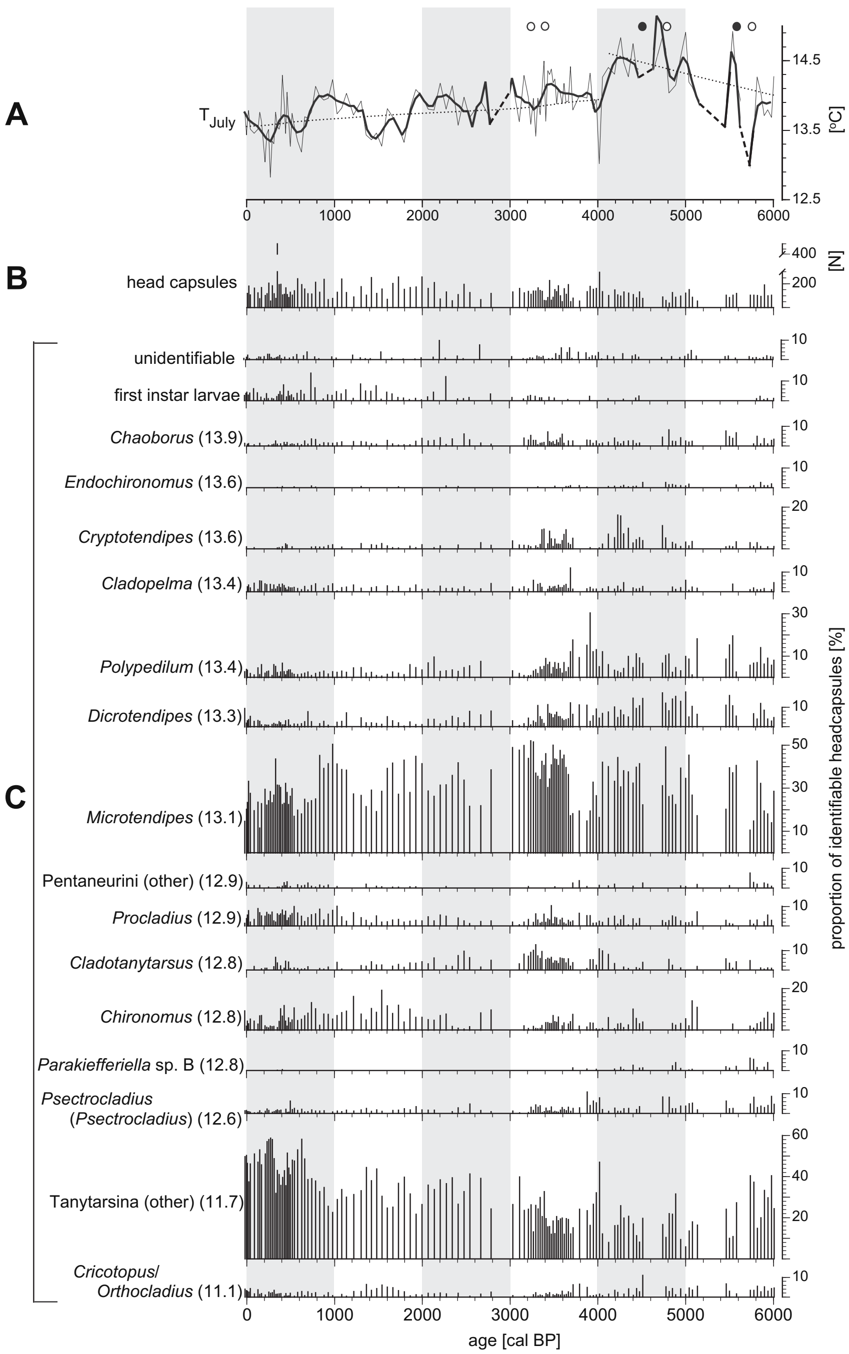

Fig. 3. (A) WA-PLS-based T_{July} reconstruction; thin line: raw data; thick line: LOESS smoothing with a 300-year span (dashed sections span gaps in data); stippled lines: linear regressions before and after change point at 4000 cal BP. Open circles indicate samples with poor analogues, closed circles indicate samples with no analogue. (B) Total number of identifiable midge remains per sample. (C) Midge assemblages; individual midge taxa are expressed as percent of all identifiable head capsules per sample. From top to bottom, taxa are arranged in order of decreasing temperature optima (listed in brackets in °C) according to Barley et al. (2006).

comparison, the variance of each of these factors is much larger across the sites in an inference model training set.

4.3. Temperature fluctuations over the past 2000 years: comparison with previous results

A number of recent paleoclimate studies in Alaska and elsewhere have focused on high-resolution reconstructions over the past two millennia (e.g., Hu et al., 2001; Loso et al., 2006; McKay et al., 2008). Comparisons of the T_{July} record from Moose Lake with other Alaskan temperature records suggest that the regional coherency observed in instrumental temperature records (e.g., Wiles et al., 1998; Gedalof and Smith, 2001; Wilson et al., 2007) extends broadly to at least 2000 cal BP. For example, climatic events such as the LIA and the Medieval Climate Anomaly (MCA; peak warmth around 1000 cal BP) occurred largely synchronously between our T_{July} record from Moose Lake (Fig. 4C) and a $\delta^{18}O$-based temperature record from Farewell Lake on the northwestern foothills of the Alaska Range (Hu et al., 2001; Fig. 4D). Local temperature minima likely associated with First Millennium AD Cooling (centered at 1400 cal BP; Wiles et al., 2008) are evident at both Farewell and Hallet (McKay et al., 2008; Fig. 4E) lakes.

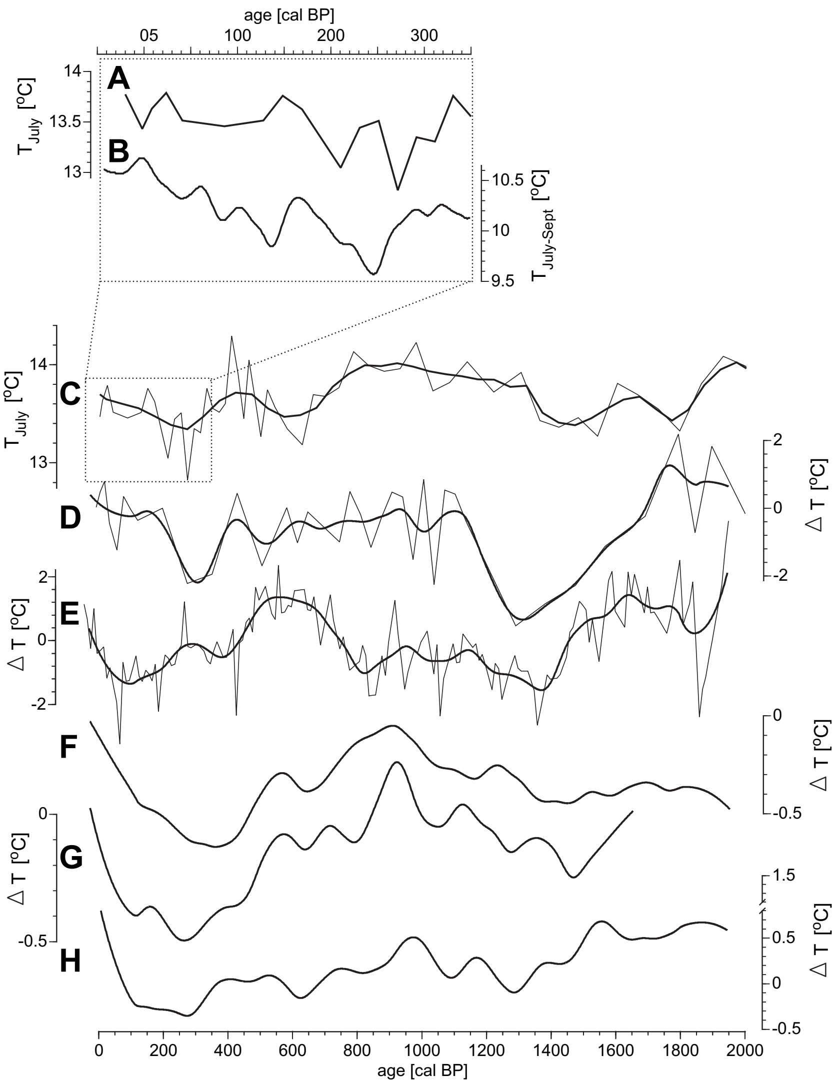

Fig. 4. (A–B) Comparison of Moose Lake T_{July} (A) and 50-year running averages of treering-inferred temperatures (July through September) from Wrangell Mountain tree line sites (B; Davi et al., 2003). (C–H) Comparison of Moose Lake T_{July} (C; thin line: raw data; thick line: LOESS with a 300-year span width) with regional temperature records (D: Farewell Lake, Hu et al., 2001; E: Hallet Lake, McKay et al., 2008) and with composite temperature records from the Northern Hemisphere (F: Moberg et al., 2005; G: Mann et al., 2008) and the Arctic (H: Kaufman et al., 2009). Regional and hemispheric temperature records are presented as LOESS-smoothed curves with a 300-year span.

Although Moose Lake also displays a temperature minimum within the first millennium AD, it appears more subdued than at the other sites. Several features in the Moose Lake temperature record also have counterparts in the composite temperature profiles from the Northern Hemisphere (Fig. 4F–H). For example, the Moose Lake record displays high temperature estimates around 1000 cal BP and maximal LIA cooling between 400 and 200 cal BP, as in other reconstructions from the Northern Hemisphere (Moberg et al., 2005; Mann et al., 2008; Kaufman et al., 2009). These similarities suggest that at centennial to millennial timescales, regional temperature in Alaska responds to large-scale climatic forcings, such as solar activity, Earth's orbital parameters, volcanism, and anthropogenic CO_2.

The Moose Lake T_{July} record is of limited value for assessing anthropogenic warming in the context of the long-term natural variability because of the relatively coarse temporal resolution and potential impacts of human activity on the lake chemistry. The youngest sample of the record spans the period of AD 1968–1972, falling within the cooler interval of the 20th-century in Alaska (Chapin et al., 2005). Although the Moose Lake T_{July} record displays an increasing trend over the past 150 years, the T_{July} values in several warm intervals of the past 6000 years were comparable to or exceeded early 20th-century values. For example, the T_{July} values during the MCA were generally higher than the early 20th-century values (Fig. 4C). This pattern contrasts with previous high-resolution temperature reconstructions from Alaska. For example, 20th-century climate was among the warmest periods of the past two millennia on the basis of $\delta^{18}O$ data from Farewell Lake (Hu et al., 2001; Fig. 4D), and a summer temperature increase of 2.0 °C over the past 150 years was inferred from a biogenic silica (BSi) record from Hallett Lake (135 km west of Moose Lake) (McKay et al., 2008; Fig. 4E). We are uncertain about the reasons for these discrepancies. One possible explanation is that our midge-based T_{July} estimates for the 20th-century were compromised by lake physical and chemical changes as a result of the railway construction and logging near Moose Lake in the early 1900's. However, the T_{July} estimate of our youngest sample matches well with the mean of instrumental temperature measurements for the same period (see Section 4.2). Other possibilities include potential proxy-specific biases of temperature inferences. For example, BSi-based temperature estimates can be skewed by better preservation of diatoms in near surface than older sediments, whereas midge-based temperature estimates may be influenced by lake depth fluctuations. Ultimately, a network of temperature reconstructions from the region is needed to differentiate climate signals from potential local effects and help explain the discrepancies among these existing temperature records.

4.4. Late-Holocene cooling trend and centennial-scale climatic oscillation over the past 6000 years: the role of orbital forcing and solar output?

Visual inspection of our T_{July} record (Fig. 3A) suggests a decreasing trend after 4000 cal BP and the possibility of an increasing trend before. Consistent with this qualitative assessment, a two-part piecewise linear regression analysis identifies a significant change point at 4000 cal BP. The slopes of linear regression models across the T_{July} data differ significantly from 0 both before and after the change point ($p < 0.001$).

The temporal resolution of our record is low prior to ca 4000 cal BP, and the T_{July} values show pronounced fluctuations. Thus it is difficult to decipher the overall trend during this interval. Several prominent peaks (≥14.5 °C) occur between ca. 5500 and 4000 cal BP (Fig. 3A), which are characterized by increases in thermophilous taxa, including *Dicrotendipes* and *Endochironomus* (Fig. 3C). Marked lithological changes occur in the Moose Lake sediments (Fig. 2A). These changes probably resulted from lake level fluctuations (Lynch et al., 2004), which may have affected midge assemblages and confounded our T_{July} estimates (Rees and Cwynar, 2010). In particular, the abundance of thermophilous taxa 5500–4000 cal BP could be alternatively attributed to lower lake levels and greater abundance of aquatic macrophytes. Higher abundance of pelagic first-instar midge larvae after 4000 cal BP could be similarly interpreted as an expansion of the lake's hypolymnion. However, no consistent change in the relative abundance of littoral and profundal taxa exists between this period of 5500–4000 cal BP and other intervals, and T_{July} fluctuations do not always coincide with lithological changes attributable to water-depth variation. For example, high T_{July} values were inferred from midge assemblages in a sediment section encompassing a transition from predominantly silt and silty gyttja (5500–5000 cal BP) to predominantly fibrous gyttja (5000–4000 cal BP), which may reflect decreased lake levels (Lynch et al., 2004). In addition, *Polypedilum*, which is commonly found in association with macrophytes (Buskens, 1987; Brodersen et al., 2001), persists at high abundance until 3700 cal BP, after the decline of the thermophilous taxa *Endochironomus* and *Dicrotendipes*. This pattern seems to indicate persistent shallow conditions following a decline in T_{July}. Furthermore, a return to silty sediments between 1000 and 500 cal BP is not associated with maximal T_{July} estimates. These discrepancies suggest that the lake-level fluctuations inferred from lithological changes do not compromise our inference of episodic high T_{July} intervals during 5500–4000 cal BP.

The broad trend of climatic cooling over the past 4000 years encompasses several intervals of relatively stable T_{July} (3900–3500, 2400–1900, 1300–800 cal BP). Late-Holocene climatic cooling has been documented with other proxy climate records from Alaska. For example, radiocarbon ages on glacially overrun wood provide a minimum age estimate of 3100 cal BP for the onset of Neoglacial cooling in the Wrangell and Saint Elias mountains (Barclay et al., 2009). Lake-sediment records suggest an even earlier Holocene onset of glacier activity between 4500 and 4000 cal BP at two high-elevation sites in the Chugach Mountains (McKay and Kaufman, 2009), similar in time to the oldest Holocene moraines of the Brooks Range (Ellis and Calkin, 1984). Furthermore, a pollen record from Grizzly Lake in the Copper River Basin displays a decreasing trend of tree abundance accompanied by increases in cold-adapted shrub (e.g., *A. viridis*) and herbaceous taxa (Tinner et al., 2006). These palynological changes suggest decreasing forest cover probably as a result of climatic cooling. The general agreement among these records provides evidence for a broad transition toward a cooler and perhaps moister late-Holocene climate in Alaska. This cooling trend may have started after the early-Holocene thermal maximum, possibly driven by decreasing summer insolation associated with the precessional cycle (Kaufman et al., 2004). However, our T_{July} record reveals prominent temperature minima between 6000 and 5500 cal BP and marked fluctuations prior to 4000 cal BP (Fig. 3A). It is possible that the low T_{July} values prior to 5500 cal BP could reflect isolated cold reversals similar to events that interrupted peak early-Holocene warmth in the Canadian Arctic (Axford et al., 2009). Additional temperature records, especially those spanning the entire Holocene, are needed to test the role of orbital variation in the evolution of summer temperature in Alaska.

Superimposed on the millennial-scale patterns described above are a number of prominent temperature drops (up to 1 °C) throughout the past 4000 years, each lasting up to several-hundred years. These intervals are centered around 4000, 3300, 1800–1300, 600, and 250 cal BP, and are characterized by subtle but consistent and simultaneous declines in all of the most thermophilous taxa in the midge assemblage (e.g., *Dicrotendipes*, *Cryptotendipes*, and *Chaoborus*). Similar temperature drops also occurred prior to 4500 cal BP, but their timing is difficult to determine because of the coarse temporal resolution of our T_{July} record during that period. Within the limit of chronological uncertainties, some (but not all) of these cooling events at Moose Lake coincide with periods of reduced solar irradiance, such as the solar minima centered on the middle and late LIA (250 and 100 cal BP), 1400 cal BP, and 3400 cal BP (Steinhilber et al., 2009). Although the co-occurrence of solar minima with cooling during the LIA is well appreciated, the role of solar output in modulating surface temperature remains controversial, partially because the effect of solar activity changes on the surface energy budget is orders of magnitude lower than those of the drivers operating over shorter timescales (e.g., clouds or volcanism) (Damon and Peristykh, 2005). Nonetheless, a number of recent paleoclimate studies have attributed decadal- to millennial-scale variation to fluctuating solar irradiance in Alaska (Hu et al., 2003; Wiles et al., 2004; Tinner et al., 2008) and elsewhere (Hegerl et al., 2003; Damon and Peristykh, 2005; Eichler et al., 2009). Thus the potential role of solar irradiance in high-latitude climate change remains an issue that warrants further research (MacDonald, 2010). Analysis of midge assemblages in lake-sediment cores from other sites is necessary to verify our results from Moose Lake and assess the potential linkages of summer temperature variation to fluctuating solar output.

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