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Short Paper

A late Quaternary chironomid-inferred temperature record from the Sierra Nevada, California, with connections to northeast Pacific sea surface temperatures

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Abstract

Chironomid remains from a mid-elevation lake in the Sierra Nevada, California, were used to estimate quantitative summer surface water temperatures during the past ~15,000 yr. Reconstructed temperatures increased by ~3°C between lake initiation and the onset of the Holocene at ~10,600 cal yr BP (calibrated years before present). Temperatures peaked at 6500 cal yr BP, displayed high variability from 6500 to 3500 cal yr BP, and stabilized after 3500 cal yr BP. This record generally tracks reconstructed Santa Barbara Basin sea surface temperatures (SSTs) through much of the Holocene, highlighting the correspondence between SST variability and California land temperatures during this interval.

Keywords: Chironomids; Holocene; Sierra Nevada; California; Temperature; Pacific Ocean; Paleolimnology; Climate change; Holocene thermal maximum

Introduction

Variations in northeast Pacific Ocean sea surface temperatures (SSTs) affect California climate by influencing the location of atmospheric pressure cells, jet-stream flow, and storm intensity (Raphael and Cheung, 1998). The conditions exhibited during the positive phases of the El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), when a weakened California current and decreased coastal upwelling result in warmer SSTs along the California coast, generally result in a warmer and wetter California by adding energy and moisture to the climate system (Cayan et al., 1998). It has been shown that northeast Pacific SSTs influence summer temperatures in California at an annual time scale (Alfaro et al., 2005), and that 20th century SST variations relating to the PDO directly affect Sierra Nevada ecosystems by modifying variations in terrestrial summer temperatures (Millar et al., 2004).

The northeast Pacific Ocean has exhibited a 1.3°C increase in SSTs during the second half of the 20th century (Di Lorenzo et al., 2005), whereas California has experienced a 1–2°C increase in air temperature during this time (Cayan et al., 2001). It is important to ascertain the long-term relationship between northeast Pacific Ocean SSTs and California temperatures to determine how this temperature shift might affect California climate through time. Previous late Pleistocene and Holocene climate reconstructions have related Pacific Ocean SSTs to California climate, but these studies focused on reconstructing water mass balance (Benson et al., 2003; Yuan et al., 2004) or effective moisture conditions (Heusser, 1998), which tend to obscure the effects of temperature and precipitation on paleoclimatic conditions. Moreover, while there have been a number of late Quaternary vegetation and climate reconstructions in the Sierra Nevada, much of the past work has focused on pollen or charcoal records (Anderson, 1990; Anderson and Smith, 1994; Brunelle and Anderson, 2003; Mensing et al., 2004), hydrologic balance of large Great Basin lakes (Stine, 1990; Davis, 1999; Benson et al., 2002a), and late Pleistocene and

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Holocene glacial fluctuations (Clark and Gillespie, 1997; Konrad and Clark, 1998). Although these studies are valuable, the methods used do not provide an independent assessment of paleotemperature. Utilizing chironomid (Insecta: Diptera) remains and a chironomid-based surface water–temperature inference model (Porinchu et al., 2002), this study provides the first independent quantitative temperature reconstruction in the Sierra Nevada spanning the entire post-glacial interval, although an earlier publication did provide a chironomid-based temperature record for the Pleistocene–Holocene transition in the region (Porinchu et al., 2003).

Chironomids are highly diverse, have relatively short life cycles, are widely distributed and are abundant in freshwater ecosystems, and the adults are mobile. Chironomids spend the majority of their life cycle under water as larvae and are very sensitive to changing limnological conditions, and as a result they are likely to have distributions in equilibrium with their environment (Walker, 2001). There are a number of recent studies that have utilized chironomid assemblages to resolve late Pleistocene and Holocene temperature fluctuations (Levesque et al., 1996; Bigler et al., 2002; Sëppa et al., 2002; Heiri and Millet, 2005). The random sample-specific error in chironomid temperature models can be 1–2°C, which is often comparable to the magnitude of the Holocene temperature fluctuations under study (Velle et al., 2005). This uncertainty can be overcome by comparing trends in chironomid assemblage variations to other factors such as lake hydrology, and by including other paleolimnological evidence in the analysis and interpretation (Bigler et al., 2002; Sëppa et al., 2002; Rosen et al., 2003; Rosenberg et al., 2004).

Study site

Hidden Lake is a small (2.0 ha), mid-elevation (2379 m above sea level) lake along the eastern slope of the Sierra Nevada, California (Fig. 1). It is 9.7 m deep. The lake overlies Cretaceous granodiorite (Giusso, 1981), has no inflow channel and has only seasonal outflow. At present, the lake is slightly alkaline (pH = 7.8), freshwater (salinity = 9.81 mg/L), and eutrophic (total P = 6 μg/L) (lake chemistry measurements were taken July 2001). The lake has two small islands in its southeast portion and a large shallow-water shelf along the southern shore extending to the northern edge of the islands (Fig. 1). The remainder of the lake forms a stratified basin, confirmed through multi-year monitoring of summer lake water temperatures using a thermistor chain. The vegetation in the modern lake catchment is a coniferous forest-woodland dominated by *Pinus contorta*, *Pinus jeffreyi*, and *Juniperus occidentalis*.

Methods

A 613-cm core (496 cm organic sediment) was recovered in February 2002 in 9.4 m of water using a modified Livingston piston corer (Wright, 1991). Lithology was stratigraphically described, and the core was sectioned at 0.5-cm intervals. Loss-on-ignition (LOI) analysis (Heiri et al., 2001) was conducted at 0.5- to 1-cm intervals.

AMS radiocarbon and tephrochronological ages were obtained along the sediment core to provide the basis for age–depth modeling (Table 1). CALIB version 5.0 and the atmospheric decadal dataset were used to convert radiocarbon dates (^{14}C yr BP) to their calibrated ages (cal yr BP; Stuiver et al., 1998). The midpoint of the 2-sigma range with the highest probability of occurrence was used to represent the cal yr BP (calibrated years before present) ages employed in the age–depth model (Fig. 2). The age–depth model is split into two separate curves: one based on four terrestrial macrofossils and an identified tephra layer in the uppermost portion of the core, and one based on three bulk sediment dates from the basal portion of the core. Bulk sediments

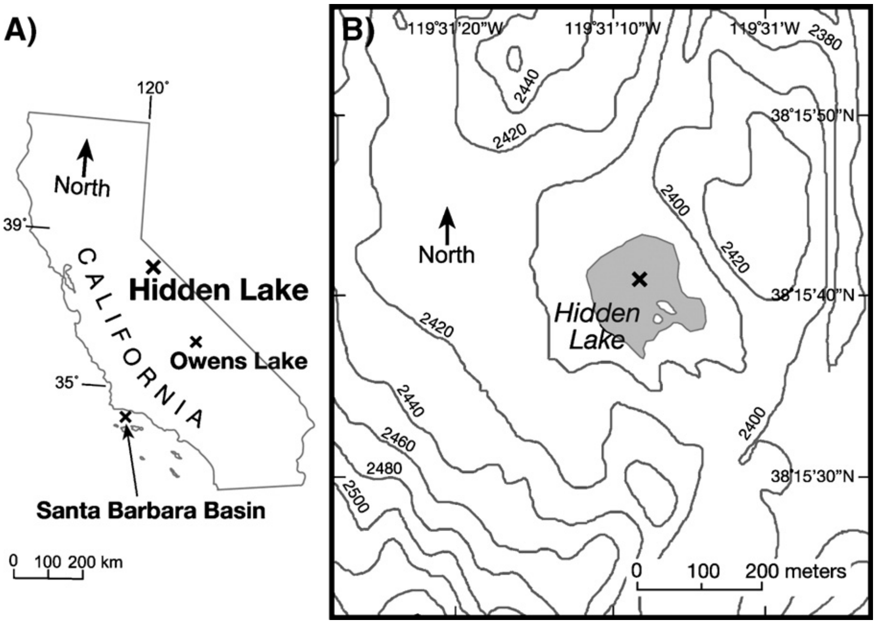

Figure 1. Map of study site along with locations of other regional records. (A) Locations of a SST record from the Santa Barbara Basin (Friddell et al., 2003a), δ^{18}O record from Owens Lake (Benson et al., 1997), and Hidden Lake. (B) Hidden Lake study site (X = coring sites).

Table 1
Age control data

Depth (cm)	Material	Lab code[a]	^{14}C yr BP ±1σ	2σ age range (cal yr BP)	Relative area under distribution	Calibrated age (cal yr BP)
143–144	Twig	Beta-179731	2540 ± 40	2487–2750	0.989	2619
247–247.5	Pine needle	Beta-179732	4460 ± 40	4964–5291	0.963	5128
310–310.5	Pine needle	Beta-179733	5880 ± 40	6621–6760	0.896	6691
347.5–351	Tsoyawata tephra[b]	–	7015 ± 45	7728–7881	0.742	7805
407–407.5	Twig	Beta-179734	8660 ± 40	9535–9741	0.998	9638
461–462	Bulk sediment	Beta-167869	9460 ± 60	10,549–10,812	0.702	10,681
473–474	Bulk sediment	Beta-168954	11,170 ± 40	12,997–13,412	0.948	13,195
493–494	Bulk sediment	Beta-167277	12,700 ± 40	14,344–15,660	1.000	15,002

[a] All AMS radiocarbon dating was conducted by Beta Analytic, Miami, Florida.

[b] Tephra identification and subsequent dating was conducted at the Microbeam Facility, GeoAnalytica Laboratory, Department of Geology, Washington State University.

represent a mix of lake and terrestrial organics, and bulk sediment dates are treated as maximum estimates of depositional age due to potential reservoir effects. Therefore, these dates are treated separately from the well-constrained portion of the chronology.

Chironomid analysis followed standard procedures outlined in Walker (2001). A minimum of 40 head capsules (average of 63 per sample) were hand picked with the aid of a Wild® 5 × dissection scope at 50 × (the sample at 487–487.5 cm contained 33 head capsules). The chironomid specimens were permanently mounted on slides and identified at 100–400 ×. Identifications were based on Wiederholm (1983), Oliver and Roussel (1983), Heiri et al. (2004), and a reference collection at UCLA. The chironomid percentage diagram was constructed using C2 version 1.4 (Juggins, 2002). Zonation of the chronology was performed on chironomid percentage abundances using ZONE version 1.2 and is based on optimal sum-of-squares partitioning (Juggins, 1991). In order to divide the chronology into statistically significant zones, the broken-stick model (Bennett, 1996) was applied to the resulting zonations using BSTICK.

The quantitative temperature reconstruction presented in this paper relied on the chironomid-based inference model of Porinchu et al. (2002) for surface water temperature developed from a 44-lake training set in the eastern Sierra Nevada. Chironomid assemblages were shown to be an excellent predictor of summer surface water temperature in the Sierra Nevada, and a robust one-component weighted-average partial least squares (WA-PLS) inference model for surface water temperature was developed (r^2 = 0.72, root mean squared error = 1.1°C and a maximum bias of 1.24°C). This model was applied to the Hidden Lake chironomid stratigraphy using WA-PLS version 1.1 (Juggins and ter Braak, 1996).

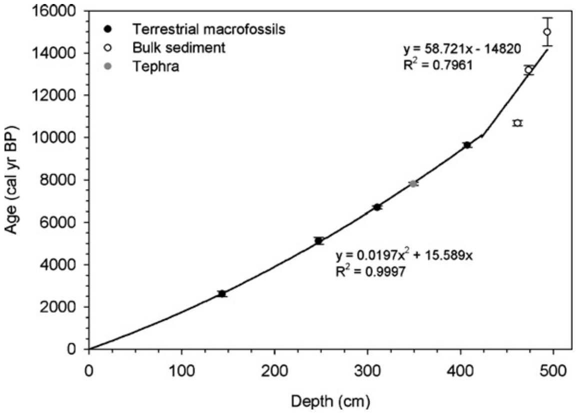

Figure 2. Age-depth model for Hidden Lake. The model uses two separate curves: a second-order polynomial spanning the first five dates and linear regression for the bulk sediment dates. Error bars are 2σ cal yr BP age range.

Results and interpretation

There were 43 distinct taxa found in the 57 samples analyzed from the Hidden Lake core. The chronology was divided into five statistically significant zones (Fig. 3). The initial post-glacial chironomid community shows a high abundance of *Corynocera oliveri* type. In the Sierra Nevada training set, *Corynocera oliveri* type is the taxon with the coldest surface water temperature optimum (Porinchu et al., 2002), indicating the occurrence of cold surface water conditions in Hidden Lake during this interval. Zones 2 and 3 showed variable abundances of thermophilous littoral taxa, including *Dicrotendipes*, signifying fluctuating water levels and the sporadic influence of a shallow-water shelf on the composition of midge fauna during times of increased lake depth.

Zone 4 was characterized by black gyttja interbedded by distinct laminations, sediment characteristics that are likely the result of deeper water conditions with insufficient benthic oxygen to support bioturbating organisms (Renberg and Segerström, 1981; Larsen and MacDonald, 1993). The increased abundance of *Chironomus* in this zone supports the presence of anoxic conditions in the deeper lake basin (Porinchu and MacDonald, 2003). Warm-water littoral species fossils, including *Microtendipes*, *Polypedilum*, *Parakiefferiella* sp. B, and *Pagastiella*, became more abundant during this time. *Chaoborus* spp. (phantom midge), an indicator of warm-water conditions (Rosenberg et al., 2004), also became more abundant in this zone.

Toward the end of Zone 4, there was a transition in the lake record. Sediments became lighter, laminations became less marked, and *Chironomus* decreased, implying the end of deep-water anoxic conditions. In addition, new warm-water littoral species, such as *Glyptotendipes*, *Pagastiella*, and *Tribelos*, began to emerge while *Microtendipes* increased substantially (Wiederholm, 1983; Olander et al., 1999). The increased relative abundance of *Chaoborus* is further evidence of lake warming toward the end of Zone 4. It is important to note the appearance of *Limnophyes*/*Paralimnophyes*, a

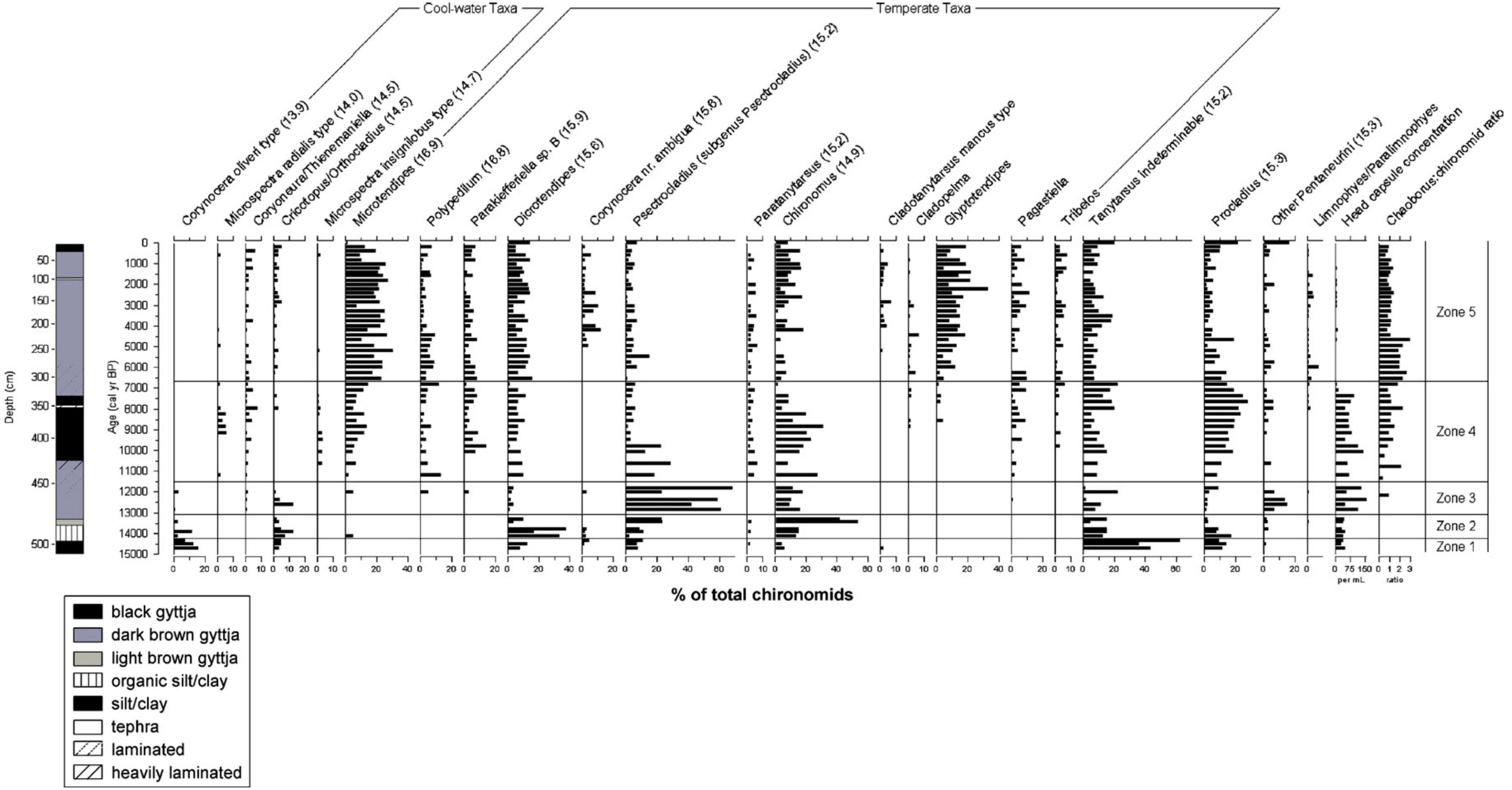

Figure 3. Chironomid stratigraphy and lithology for Hidden Lake. Taxa are grouped as ‘cool-water taxa’ and ‘temperate taxa’ according to their surface water temperature optima. Water temperature optima values are in parentheses for species that were present in >20% of lakes in the calibration set and determined in Porinchu et al. (2002). Other warm-water taxa were grouped based on their surface water temperature optima as defined in the literature and include *Cladotanytarsus mancus* type, *Cladopelma*, *Glyptotendipes*, *Pagastiella*, and *Tribelos* (see Discussion for specific citations on each taxon). Head-capsule concentration and the *Chaoborus*-to-chironomid ratio are also presented in the stratigraphy.

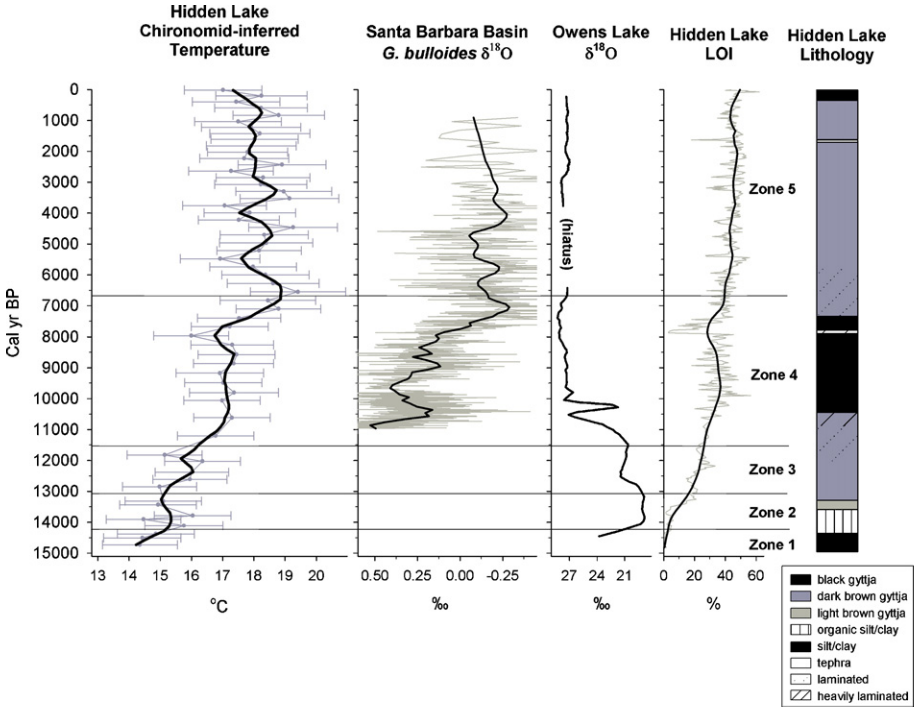

Figure 4. Chironomid-based summer surface water temperature reconstruction for Hidden Lake with a LOWESS smoother (span = 0.10). The Hidden Lake temperature curve is accompanied by a LOWESS-smoothed (span = 0.05) *Globigerina bulloides*-based $\delta^{18}O$ reconstruction from the Santa Barbara Basin (Friddell et al., 2003b), a LOWESS-smoothed (span = 0.10) Owens Lake $\delta^{18}O$ curve (Benson et al., 2002b), a LOWESS-smoothed (span = 0.10) Hidden Lake LOI curve, and Hidden Lake lithology. The Owens Lake dating model has been slightly modified by the study's authors since first publication.

semi-terrestrial chironomid taxon indicative of the emergence of a lakeside marsh that likely developed along the lake's edges as water levels receded (Wiederholm, 1983).

The inferred drop in lake level and warmer water conditions lasted from ~7200 to ~4500 cal yr BP. After ~4500 cal yr BP, *Chironomus* abundance increased as anoxic conditions returned to the lake. The increase in *Cladotanytarsus mancus* type also supports the influence of deeper lake conditions during this time (Wiederholm, 1983). The sustained presence of cool-water taxa through Zone 5 is evidence of the existence of cool deep water, likely resulting from strong stratification within the lake system.

Temperature reconstruction

Reconstructed summer surface water temperatures at Hidden Lake range from 14.3 ± 1.2°C at lake initiation to 19.4 ± 1.5°C at ~6500 cal yr BP (Fig. 4). Specific errors range from ± 1.2°C at ~12,400 cal yr BP to ± 1.6°C at ~1420 cal yr BP. There was a general trend of increasing temperatures (~3°C) from lake initiation until ~10,600 cal yr BP. Temperatures reached a plateau of 16.8–17.4°C by ~10,600 cal yr BP, and remained relatively steady until just before 8000 cal yr BP. At ~8000 cal yr BP, chironomid-inferred summer surface water temperatures at Hidden Lake experienced a 1.3°C drop, then sharply rose 3.4°C to their Holocene maximum of 19.4°C at ~6500 cal yr BP, 2.3°C greater than chironomid-inferred modern surface water temperature. From 6500 to 3500 cal yr BP, the temperature record exhibited high-amplitude peaks (centered at ~6500, ~4500, and ~3500 cal yr BP) and troughs (centered at ~5500 and ~3800 cal yr BP) in temperature. The range of chironomid-inferred temperatures for the mid-Holocene peaks was 19.1–19.4°C, and the temperature of the mid-Holocene troughs was 17.1°C. The remainder of the chronology is relatively stable, with slightly cooler summer surface water temperatures that gradually decrease until the present. Chironomid-inferred surface water temperatures were only 0.2°C lower than mean measured summer surface water temperatures for the summer of 2002 (hourly temperatures logged through the summer), indicating that temperature estimates accurately predict modern measured Hidden Lake temperatures. Error estimates are often larger than temperature changes during the mid- and late Holocene, a common characteristic of chironomid-based Holocene temperature reconstructions (Velle et al., 2005). However, contiguous samples exhibit consistent temperature trends that do not follow shifts in LOI or sediment lithology through this interval (Fig. 4), suggesting that peaks and troughs are robust estimations of relative temperature changes.

Discussion

Comparison to other regional records

The Hidden Lake reconstruction was compared to other regional records to assess if the observed trends were catchment-specific. Pollen evidence suggests that the late Pleistocene and early Holocene in the Sierra Nevada were cooler and drier than present (Davis et al., 1985; Anderson, 1990), and the Hidden Lake record supports these inferences indicating low temperatures and generally lower, though fluctuating, lake levels during this time. Furthermore, late Pleistocene warming accounted for the bulk of the temperature increase during the Pleistocene–Holocene transition in Hidden Lake (~3.0°C). This compares favorably with a chironomid-based temperature reconstruction from a high-elevation lake in the Sierra Nevada, where the bulk of warming during this transition also occurred before 10,600 cal yr BP, and was of a similar magnitude during this time interval (~3.3°C) (Porinchu et al., 2003). Following the Pleistocene–Holocene transition, relatively cool and wet conditions prevailed at Hidden Lake from ~10,600 to ~7500 cal yr BP. This is supported by TIC (total inorganic carbon) and δ^{18}O evidence from Owens Lake, California, which suggest regionally wet conditions from 10,000 to 8000 cal yr BP (Benson et al., 1997; Fig. 4).

The warm and dry mid-Holocene conditions in Hidden Lake culminated with a Holocene thermal maximum at ~6500 cal yr BP. This coincided with the warmest climatic conditions within the Santa Barbara Basin from ~7800 to 5400 cal yr BP (Pisias, 1978). Hot and dry conditions were also indicated by the disappearance of Great Basin pikas, which cannot survive high desert heat, by ~7850 cal yr BP (Grayson, 1993) and by submerged stumps in Lake Tahoe (indicating lower water levels) from 6300 to 4850 cal yr BP (Lindstrom, 1990). Drought conditions prevailed at Pyramid Lake in western Nevada from ~7600 to ~3500 cal yr BP, with the lowest lake levels occurring between ~7600 and ~6300 cal yr BP (Benson et al., 2002a; Mensing et al., 2004). Owens Lake displayed a hiatus in sediment deposition between ~6500 and ~4000 cal yr BP, indicating that water levels were below coring elevation (Benson et al., 1997; Fig. 4). Finally, using a regional climate model, Diffenbaugh and Sloan (2004) demonstrated that at ~6000 cal yr BP summers in the western United States were 1 to 2.5°C warmer than today due to increased amplitude of seasonal insolation.

Temperature estimates in the Hidden Lake reconstruction show a Holocene summer thermal maximum that was likely 2.3°C higher than modern temperatures, comparing well with climate-model estimates for 6000 cal yr BP. In addition to inferring higher mid-Holocene summer temperatures, fluctuations in the Hidden Lake record suggest a more variable climate from 6500 to 3500 cal yr BP. This is supported by a SST record from the Santa Barbara Basin (SBB) that indicates a warmer but more variable mid-Holocene (~7000–3500 cal yr BP), likely due to a persistent PDO warm phase and increased intensity of ENSO events (Friddell et al., 2003a), as well as other records (see below).

Hidden Lake water levels increased by ~4500 cal yr BP, and temperatures stabilized at slightly lower levels by ~3500 cal yr BP. These relatively cooler and moister conditions are supported by a general transition of meadows to peats in the southern Sierra Nevada at ~4500 cal yr BP (Anderson and Smith, 1994), and increased lake levels at Pyramid Lake after ~3500 cal yr BP (Benson et al., 2002a).

Connection with northeast Pacific Ocean SSTs

Since northeast Pacific Ocean SSTs have been shown to affect terrestrial temperatures at annual to multi-decadal time scales (Millar et al., 2004; Alfaro et al., 2005), it can be expected that the general temperature trends should correspond at the centennial to millennial time scales. In order to test this long-term connection, the Hidden Lake temperature record was compared to a Holocene *Globigerina bulloides*-based δ^{18}O record from the SBB, where lower δ^{18}O values imply higher SSTs (Friddell et al., 2003b; Fig. 4). The general trends in both curves correspond well. Both curves show generally lower temperatures in the early Holocene. The curves then dip in temperature at ~8000 cal yr BP and show similar slope in rising to their respective Holocene thermal maxima. Both curves also exhibit a more variable mid-Holocene. The late Holocene becomes more stable, with generally lower and slightly decreasing temperatures after ~3500 cal yr BP. The reconstructions are slightly offset, with SSTs leading Hidden Lake temperatures by ~500 yr. This could be due to differences within the chronologies. For example, the SBB record uses a surface reservoir age of 710 yr (Friddell et al., 2003a).

The high-amplitude mid-Holocene climate variability that is exhibited in both the SBB SST record and the Hidden Lake chironomid sequence can be seen in other terrestrial records in the Sierra Nevada. A δ^{18}O record from Pyramid Lake exhibits extreme fluctuations from ~7600 to 6500 cal yr BP and further fluctuations from 6500 to 3900 cal yr BP of higher magnitude than fluctuations in the late Holocene (Benson et al., 2002a). A δ^{18}O record from Owens Lake displays high-amplitude oscillations from 7700 to 6500 cal yr BP, but the record is interrupted by a sediment hiatus due to low water levels from ~6500 to 3500 cal yr BP (Benson et al., 1997; Fig. 4). Finally, there is ample anthropological evidence of increased climate variability in the entire Pacific basin from ~8000 to 3000 cal yr BP, based on human settlement patterns in North and South America, East Asia, Australia, and other geographic regions (Sandweiss et al., 1999).

Conclusions

This study provides the first independent quantitative temperature reconstruction in the Sierra Nevada using the paleolimnological approach to span the late Pleistocene and Holocene. Climate inferences from the Hidden Lake reconstruction follow broad trends in other terrestrial records from the region, although the mid-Holocene appears more variable in the Hidden Lake chironomid-inferred temperature record than in other terrestrial records. This may reflect the strength of subfossil chironomids in resolving variations in surface water temperature through time. The record suggests that Sierra Nevada Holocene temperatures are directly influenced by northeast Pacific Ocean SSTs at centennial to millennial time scales, with both records showing similar trends through the Holocene. Evidence of higher climate variability in the Sierra Nevada and the SBB during the warm mid-Holocene suggests that California climate may become more variable with more intense ENSO events as the northeast Pacific Ocean continues to warm.

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