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A 2000-yr reconstruction of air temperature in the Great Basin of the United States with specific reference to the Medieval Climatic Anomaly

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ABSTRACT

A sediment core representing the past two millennia was recovered from Stella Lake in the Snake Range of the central Great Basin in Nevada. The core was analyzed for sub-fossil chironomids and sediment organic content. A quantitative reconstruction of mean July air temperature (MJAT) was developed using a regional training set and a chironomid-based WA-PLS inference model ($r^2_{jack} = 0.55$, RMSEP = 0.9°C). The chironomid-based MJAT reconstruction suggests that the interval between AD 900 and AD 1300, corresponding to the Medieval Climate Anomaly (MCA), was characterized by MJAT elevated 1.0°C above the subsequent Little Ice Age (LIA), but likely not as warm as recent conditions. Comparison of the Stella Lake temperature reconstruction to previously published paleoclimate records from this region indicates that the temperature fluctuations inferred to have occurred at Stella Lake between AD 900 and AD 1300 correspond to regional records documenting hydroclimate variability during the MCA interval. The Stella Lake record provides evidence that elevated summer temperature contributed to the increased aridity that characterized the western United States during the MCA.

Introduction

It is well documented that high-elevation regions of the world are exceedingly susceptible to anthropogenic climate change (Bradley et al., 2004). The western United States, characterized by numerous mountain ranges, has been impacted by elevated temperature and decreases in effective moisture in recent decades (Westerling et al., 2006; Barnett et al., 2008; Williams et al., 2010). A better understanding of the potential impacts of increased warmth and aridity to the environments of western United States, and the Great Basin in particular, can be gained from proxy climate records (Mensing et al., 2008; Williams et al., 2010). Although hydroclimate variability in the Great Basin and adjacent regions during the last two millennia has been well documented (Cook et al., 2004; MacDonald, 2007; Mensing et al., 2008; Conroy et al., 2009; Woodhouse et al., 2010; Routson et al., 2011), much of this research has been focused upon reconstructions of the two 'megadroughts' identified by Stine (1994) and the precipitation anomalies that occurred during the Medieval Climate Anomaly (MCA) (AD 900–1300). The MCA is characterized by a spatially heterogeneous response in moisture and temperature; however, the MCA is generally associated with warmer conditions in the Northern Hemisphere (Hughes and Diaz, 1994; Mann et al., 2008; Diaz et al., 2011). Unfortunately, as noted by Woodhouse et al. (2010) and Routson et al. (2011), quantitative, high-resolution temperature reconstructions spanning the last two millennia in the Great Basin of the United States are sparse, making it difficult to explicitly identify the sensitivity of the region to hemispheric temperature patterns and the degree to which temperature changes contributed to intensifying regional aridity during the last two millennia.

Proxy-based and modeled temperature reconstructions from the Great Basin, spanning the last two millennia, are qualitative, limited in their temporal resolution, or have large sample specific errors (Tausch et al., 2004; Stevens et al., 2008; Louderback and Rhode, 2009; Salzer et al., 2009). The hydroclimate of arid and semi-arid environments such as the southwestern United States and the Great Basin is greatly influenced by temperature with temperature playing a critical role in controlling effective moisture and exacerbating drought through reduced snowpack and earlier peak run-off (Cayan et al., 2010; Shinker and Bartlein, 2010; Woodhouse et al., 2010). For this reason, improving our understanding of thermal regimes during the last two millennia, specifically the MCA, is critical. Increasing the number of lengthy and detailed quantitative records describing the regional response of Great Basin climate and vegetation to past climate perturbations, with a specific emphasis placed on prolonged warm intervals, will expand

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our knowledge of the mechanisms driving climate variability in the Great Basin under warmer conditions and possibly provide insight into future conditions at a regional scale (Mock and Brunelle-Daines, 1999; Woodhouse et al., 2010).

In this paper we apply a chironomid-based inference model for mean July air temperature (MJAT) (Porinchu et al., 2010) and develop a detailed, sub-centennial, quantitative reconstruction of thermal conditions for Stella Lake in Great Basin National Park (GBNP) that spans the last two millennia. We use loss-on-ignition (LOI) to make qualitative inferences of lake productivity (Heiri et al., 2001). This study expands on our earlier work describing Holocene Thermal Maximum (HTM) conditions in GBNP (Reinemann et al., 2009) and provides a much needed, well-constrained (sub-centennial resolution), paleotemperature record for the Great Basin spanning the last 2000 yrs. This quantitative reconstruction will improve our understanding of the temporal patterns of past climate change during the MCA, an interval characterized by significant regional hydroclimate variability. The results from Stella Lake are compared to existing paleoclimate reconstructions from the Great Basin and hemispheric temperature compilations. Our intention is to describe how thermal conditions at Stella Lake in the central Great Basin have changed during the last two millennia, with specific reference to the MCA.

Study region

The topography and atmospheric dynamics associated with the Great Basin create a highly complex and variable climate (Wise, 2012). On a local scale topographic relief greatly influences climate; steep temperature and precipitation gradients are associated with elevation (Houghton et al., 1975). The valley floors experience summer, June, July, and August (JJA), temperatures of ~22.0°C and winter, December, January, and February (DJF), temperatures of −1.0°C, while high elevations are characterized by summer temperatures of ~13.5°C and winter temperatures of −7.0°C (WRCC, 2008). Annual precipitation in the Great Basin is strongly delineated in space and time. Maximum precipitation in the southeastern Great Basin occurs during the summer and is typically associated with the North American Monsoon (NAM), while the southwestern Great Basin experiences a precipitation maximum during the winter months (Mock, 1996; Wise, 2012). The northern Great Basin experiences a winter and early spring maximum, with lesser amounts during the summer resulting from convectional thunderstorms (Mock, 1996; Wise, 2012). The Great Basin is also characterized by low amounts of effective moisture (precipitation–evaporation) due to the relatively high temperatures and low moisture availability (Shinker and Bartlein, 2010). Although, intra-annual variability in the Great Basin is driven by seasonal changes, the inter-annual climate variability in the Great Basin is driven mostly by the relationship between the tropical Pacific through ENSO and the northern Pacific through the PDO (Wise, 2012).

Study site

The lake sediment record discussed in this study was obtained from Stella Lake (39°00.324′N, 114°19.140′W), a small (2 ha), sub-alpine lake on the east side of the Snake Range (Fig. 1). Stella Lake is located in the central Great Basin, an area with a limited number of high elevation paleoclimate records available. Stella Lake is situated near the head of the Lehman Creek drainage basin at 3170 m asl (Reinemann et al., 2011). Stella Lake is underlain by quartzite of Precambrian and Cambrian ages, with late Quaternary glacial till present at the surface (Whitebread, 1969). Osborn and Bevis (2001) suggest that the most recent glacial advance in the Lehman Creek drainage is associated with Angel Lake moraines of Late Wisconsinan age (Wayne, 1983).

Material and methods

The sediment sequence recovered from Stella Lake consists of a 328-cm-long composite core, which is comprised of a modified Livingstone piston core (GB-SL-07-LC2) and a 60-cm surface core preserving the flocculent surface sediment (GB-SL-07-PT1), both taken from the center of Stella Lake at a depth of approximately 1.5 m in August 2007. The flocculent surface sediment was sectioned in the field at a 0.25-cm interval and the piston core was sectioned in the lab at a 0.25-cm interval. Based on the observation of the uppermost sediment during collection of the core and previous core based studied in the western US, bioturbation was seen to be minimal, justifying the sampling interval (Porinchu et al., 2007, 2010). The sediment cores recovered with the plastic tube and the Livingstone barrel were matched using stratigraphy, LOI, and chironomid assemblages to form a single composite core.

A total of eight accelerator mass spectrometry (AMS) ^{14}C dates constrain the core; however, chronological control for the last two millennia was based on the uppermost six AMS ^{14}C dates obtained on samples consisting of either small wood fragments or conifer needles (Table 1). The radiocarbon dates were provided by three laboratories

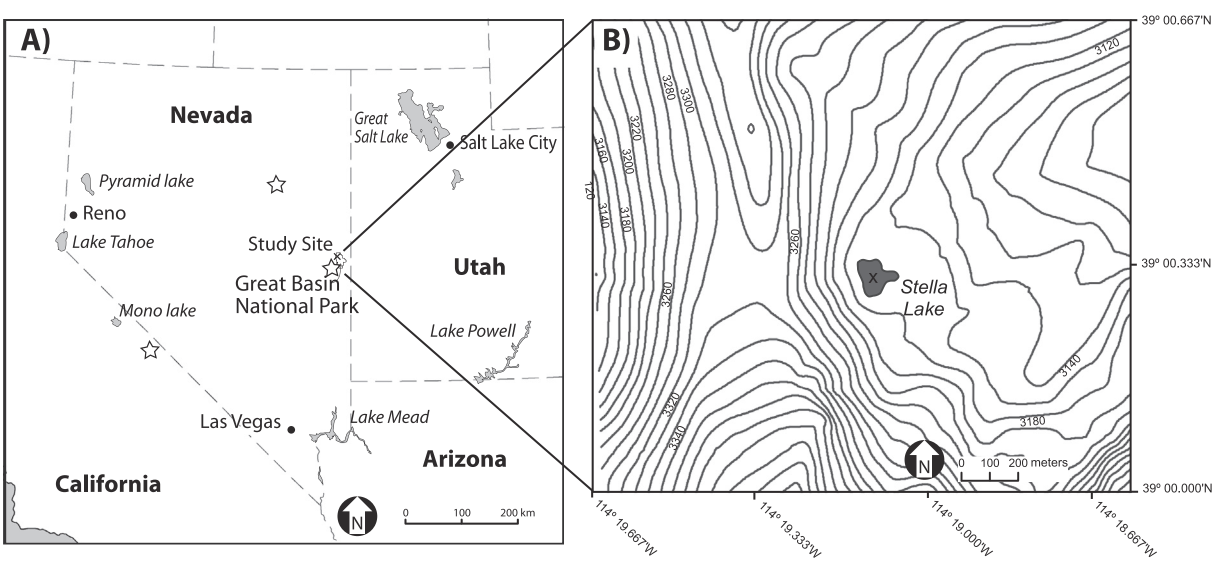

Figure 1. Location map of the study area and study site. (A) Overview map of western United States with major cities and lakes for reference. Sites of tree ring chronologies from Salzer et al. (2009) are marked with a star. Location of Great Basin National Park shown surrounding study site, Stella Lake = x. (B) Stella Lake study site located within GBNP (x = coring location).

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Table 1
AMS ^{14}C dates used for the Stella Lake core. The National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) (Woods Hole, Massachusetts), Beta Analytic Inc. (Miami, Florida), and UGA Center for Applied Isotope Studies (Athens, Georgia) provided the dates. Lab code refers to NOSAMS sample number (OS-), UGA Center for Applied Isotope Studies sample number begins with 119, or the Beta Analytic sample number begins with 262.

Lab code	Depth in core (cm)	Material	^{14}C yr BP	±	Age (AD/BC) 2σ range
OS-65913	33.00	Conifer needle	185	30	1651 to 1954
11919	51.00	Conifer needle	360	20	1456 to 1631
11920	60.5	Bark fragment	420	20	1436 to 1487
262566	70.25	Conifer needle	1250	40	675 to 873
262567	77.50	Conifer needle	1640	75	240 to 571
OS-64648	115.00	Twig	2080	35	−195 to −2

(Table 1). CALIB version 6.1.0 was used to convert radiocarbon dates (^{14}C yr BP) to their calibrated ages (AD/BC) (Reimer et al., 2009). The age-depth model was constructed using the freely available R code package BACON (Bayesian Accumulation Model) developed by Blaauw and Christen (2011). The routine uses IntCal09 (Reimer et al., 2009) and the calibration curves for each date to concentrate on modeling accumulation rates based on a gamma autoregressive process (Blaauw and Christen, 2011). The method uses a Markov chain Monte Carlo approach with a self-adjusting algorithm (Christen and Fox, 2010). The BACON program assumed a gamma distribution (shape = 3) for sedimentation rates with a mean of 15 yr cm^{-1}. The model also included the prior condition that the surface was AD 2007 ± 1. This provides a goodness-of-fit for each depth with the age reported as calibrated ages (AD/BC).

LOI analysis at 550°C was completed for the length of the core on 0.25 cm thick samples every 0.5 cm (Heiri et al., 2001). Chironomid analysis followed Walker (2001). Sub-fossil chironomid remains were analyzed from 0.25 cm thick samples every 1.0–1.25 cm. The chironomid remains were handpicked using a Zeiss Stemi 2000-C Stereo microscope and permanently mounted on slides using Entellen®. Identification of the sub-fossil remains was conducted at 400× magnification and was based on Brooks et al. (2007) and an extensive reference collection of sub-fossil midge remains housed at The Ohio State University. A minimum of 45 head capsules, obtained from 0.25–2.0 mL of sediment per sample, were used in all statistical analyses (Heiri and Lotter, 2001; Quinlan and Smol, 2001).

The chironomid percentage diagram was plotted using C2 (Juggins, 2003) and was based on the relative abundance of all chironomid remains. Optimal sum of squares partitioning, implemented by the program ZONE version 1.2 (Juggins, 1992), was used to identify statistically significant zones in the midge stratigraphies. The statistical significance of the zones was determined using a broken stick model approach (Bennett, 1996) and implemented using the program BSTICK (J.M. Line and HJ.B Birks, unpublished program). The subfossil assemblages present in Stella Lake were plotted passively with the training set lakes using correspondence analysis (CA). Correspondence analysis is a form of indirect gradient analysis that can be used to determine if downcore assemblages are well represented in the training set. Lastly, a form of indirect gradient analysis, detrended correspondence analysis (DCA), was used to assess the degree of compositional turnover between samples. The relative abundance data used in the ordination analyses was square-root transformed to maximize the 'signal to noise' ratio (Prentice, 1980). All ordination analyses were implemented using CANOCO version 4.5 (ter Braak and Šmilauer, 2002).

A two-component Weighted-Averaging Partial Least Squares (WA-PLS) inference model ($r^2_{jack} = 0.55$, RMSEP = 0.9°C, maximum bias = 1.66°C) (Porinchu et al., 2010) based on 79 lakes and 54 midge taxa was applied to the chironomid stratigraphies from Stella Lake to develop a chironomid-based mean July air temperature (MJAT) reconstruction. The sample specific error estimates were calculated using the program C2 (Juggins, 2003). Further description of the training set and inference model is available in Porinchu et al. (2007, 2010). This inference model has been used to develop quantitative temperature reconstructions for the Great Basin during the 20th century (Porinchu et al., 2010; Reinemann et al., in press) and the mid-Holocene (Reinemann et al., 2009). Finally, the reconstructions were examined for significance by the tests outlined in Telford and Birks (2011). According to Telford and Birks (2011) a reconstruction can be considered statistically significant if it explains more than 95% of the variance in the fossil data than that of the 999 reconstructions trained on random environmental data drawn from a uniform distribution.

Results

Chronology and loss-on-ignition

The chronology, established by six AMS radiocarbon dates, indicates that the last two millennia in the Stella Lake core are captured in the upper 100 cm of sediment, providing an average sediment accumulation rate of approximately 0.046 cm yr^{-1} (Table 1, Fig. 2). The age-depth model and sampling interval result in a sub-centennial sample resolution (~25 yr per sample). The uncertainty in the age-depth model as indicated by the 95% confidence bands is relatively constrained in the MCA portion of the core, but less so for the last 500 yr. The core consists primarily of organic rich gyttja, with dark organic bands interspersed throughout the core. Sediment organic content, as estimated by LOI, varies between 25% and 35% between AD 0 and AD 1400. An abrupt shift to extremely low LOI (~8%) occurs at approximately AD 1550. This abrupt drop in LOI values is associated with a dense and dark 5.0-cm layer of sediment characterized by extremely low chironomid head capsule concentration and large amounts of macroscopic charcoal likely reflecting increased erosion or a mass wasting event due to fire. This layer is assumed to have been instantaneously deposited for the purposes of age-depth modeling. Organic content steadily increases in the post-AD 1550 interval reaching a present day value of ~54%.

Chironomid community change

A total of twelve midge taxa were identified in the Stella Lake core (Fig. 3). Taxon richness varies throughout the core, with samples consisting of between eight and ten extant taxa. Head capsule concentrations vary between 45 and 700 head capsules per mL. Significant changes in sub-fossil chironomid community composition resulted in four zones (SL-I to SL-IV), representing distinct transitions. The midge community present in Zone SL-I (BC 100–AD 550) is dominated by *Cladotanytarsus mancus* group and *Tanytarsus* with lesser amounts of *Procladius*, and *Tanytarsus* type *H*. This zone is also characterized by a slight decreasing trend in the relative abundance of *Chironomus*. An abrupt shift in community composition occurs in Zone SL-II (AD 550–1300) with the contribution of *C. mancus* group and *Tanytarsus* decreasing and a large increase in *Psectrocladius semicirculatus/sordidellus* (~40%) and *Pentaneurini* (~10%) occurring. This zone is also characterized by the peak of *Corynoneura/Thienemanniella*, which reaches a core maximum of ~10% at AD 600. The midge community in Zone SL-III (AD 1300–1650) is characterized by high relative abundances of *C. mancus* group, and an increasing abundance of *Tanytarsus*. Finally, the midge community present in Zone SL-IV (AD 1650–present) is characterized by a dominance of *Tanytarsus* with lesser amounts of

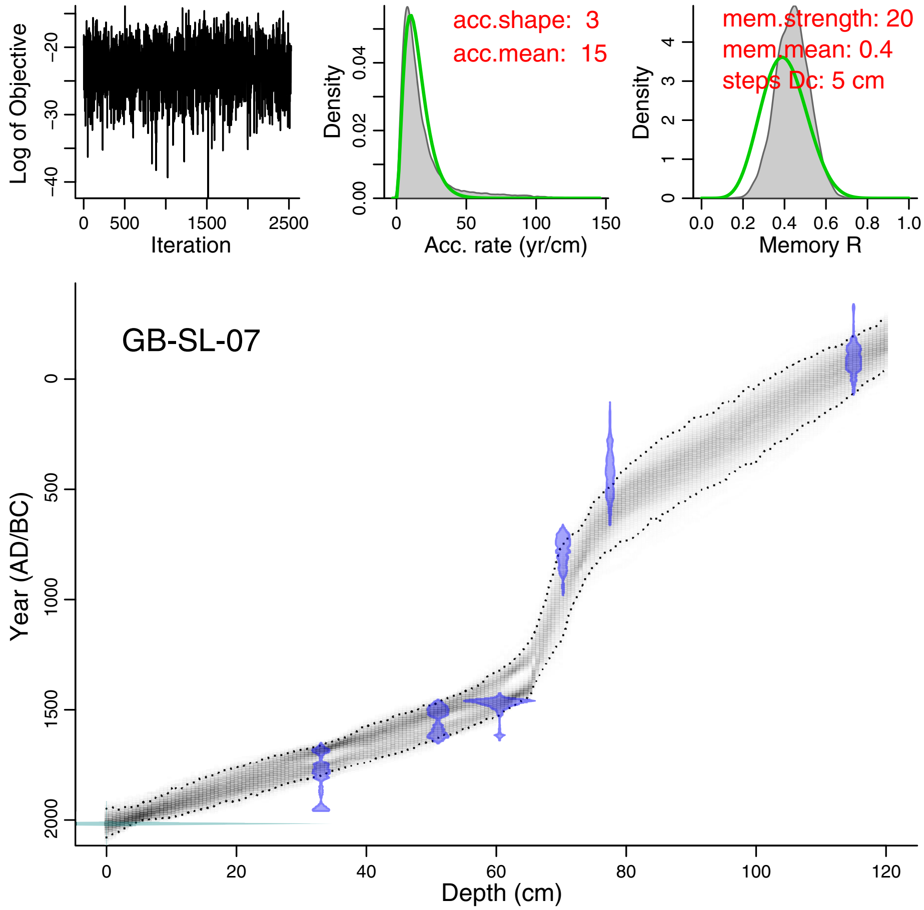

Figure 2. Age-depth model for the sediment core from Stella Lake (gray), overlaying the calibrated distributions of individual dates (blue). Gray dots indicate the model's 95% probability intervals as outputted by BACON routine (Blaauw and Christen, 2011). The upper left inset shows the iteration history, the middle inset shows the prior (green line) and posterior (gray area) of the sediment accumulation rate (yr/cm), and the right inset shows the prior (green line) and posterior (gray area) of the memory (1-cm autocorrelation strength). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

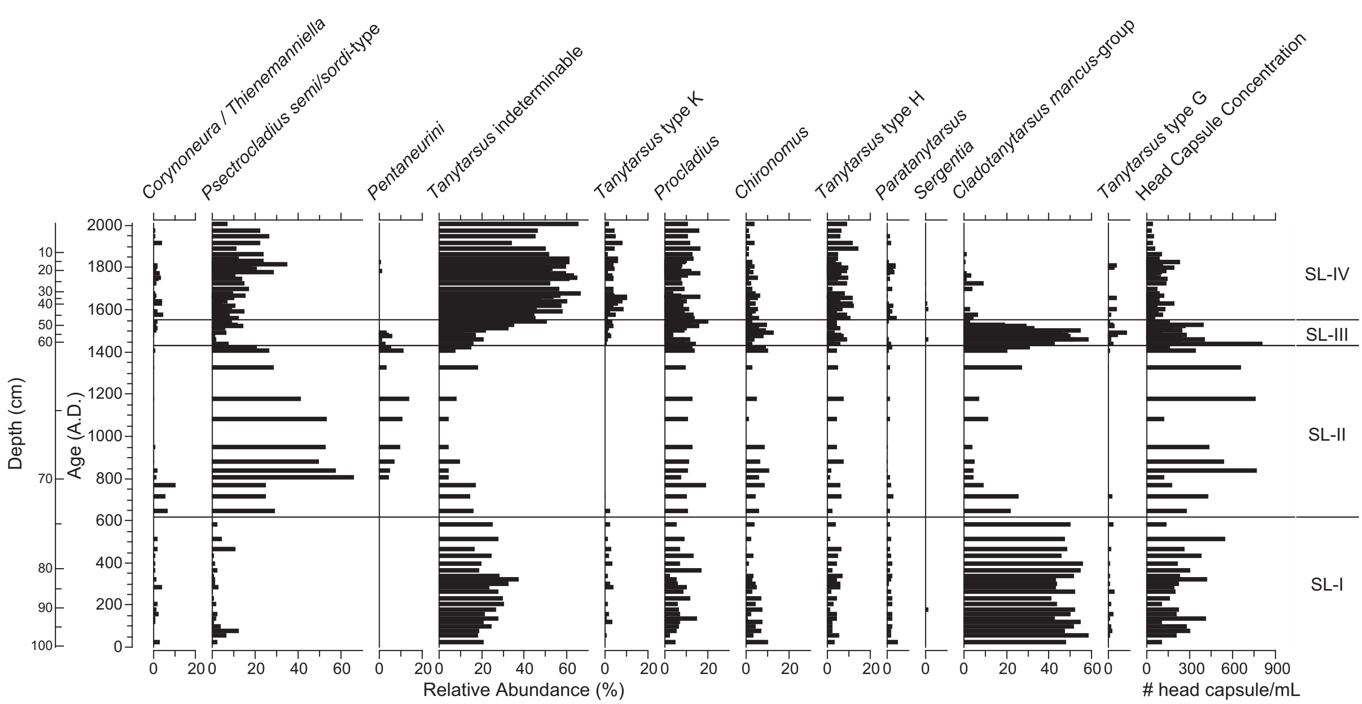

Figure 3. Chironomid relative abundance diagram for Stella Lake. Taxa have been arranged according to their MJAT optima from the chironomid-based inference model, with decreasing optima temperature from left to right. *Psectrocladius semi/sordid*-type = *Psectrocladius semicirculatus/sordidellus*.

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P. semicirculatus/sordidellus, *Procladius*, and *Tanytarsus* type *H*. This zone is also characterized by the near extirpation of *C. mancus* group. Furthermore, the four zones exhibit large changes in the concentration of head capsules. Zone SL-I has a fairly uniform concentration of 200 head capsules mL^{-1}, while Zone SL-II was characterized by large sample-to-sample variability with head capsule concentrations fluctuating between 50 and 700 head capsules mL^{-1}. Zone SL-III exhibits a decrease in concentrations from 600 to 200 head capsules mL^{-1}. Lastly, Zone SL-IV has a uniform concentration of approximately 100 head capsules mL^{-1}.

Chironomid-based MJAT reconstruction

The subfossil midge assemblages from Stella Lake were plotted passively against the assemblages in the Intermountain West training set using CA to determine if the midge communities are represent in the regional training set (Fig. 4). The CA bi-plot indicates that the composition of the midge communities over the last 2000 yr at Stella Lake is located within the ordination space captured by the calibration set. The taxa present in Stella Lake are well-represented and characterized by the calibration set with all twelve chironomid taxa comprising the Stella Lake chironomid stratigraphy present in the Intermountain West training set (Porinchu et al., 2010); therefore, the MJAT reconstructions can be considered very reliable (Birks, 1998). Values ranging between 12 and 75 for Hill's N2 diversity index (Hill, 1973) provide added support that the quantitative chironomid-based MJAT reconstructions can be considered robust (Birks, 1998). The MJAT reconstruction also passed the test for significance outlined by Telford and Birks (2011), with a significance of $p = 0.002$ (Fig. 5). The chironomid-inferred MJAT reconstruction for Stella Lake is presented in Figure 6. The sample-specific error estimates associated with the MJAT inferences varied between 1.0°C and 1.7°C.

Application of a two-component WA-PLS inference model for MJAT to the newly developed sub-fossil chironomid stratigraphy from Stella Lake provides much greater detail of the magnitude and timing of the fluctuations of MJAT during the last two millennia than available previously (Reinemann et al., 2009). The average chironomid-inferred MJAT for the last two millennia is 11.0°C (Fig. 6). Between AD 0 and AD 600 the MJAT remained low, approximately 1.0°C below the 2000-yr average. The interval between AD 800 and AD 1200 experienced an increase in temperatures to approximately 0.4°C above the long-term mean. Starting at AD 1200 and continuing to AD 1600 the record was characterized by air temperatures approximately 0.8°C below average. The chironomid-inferred MJAT rose to approximately 12°C at AD 1600, approximately 0.8°C above the late Holocene average and remained

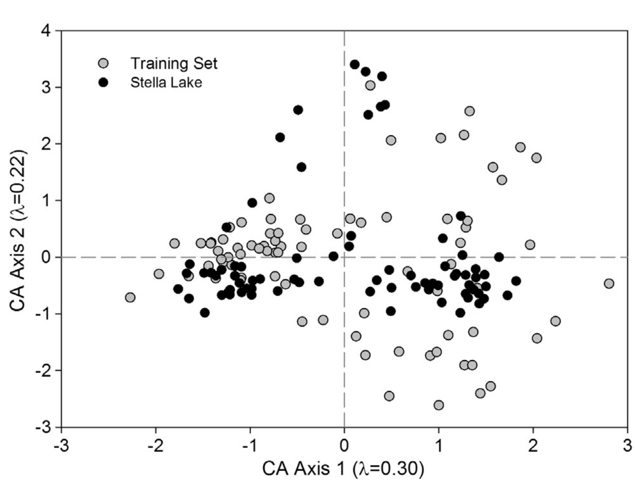

Figure 4. Correspondence analysis (CA) passively plotting midge assemblages from Stella Lake with chironomid assemblages present in the Intermountain West training set (Porinchu et al., 2010).

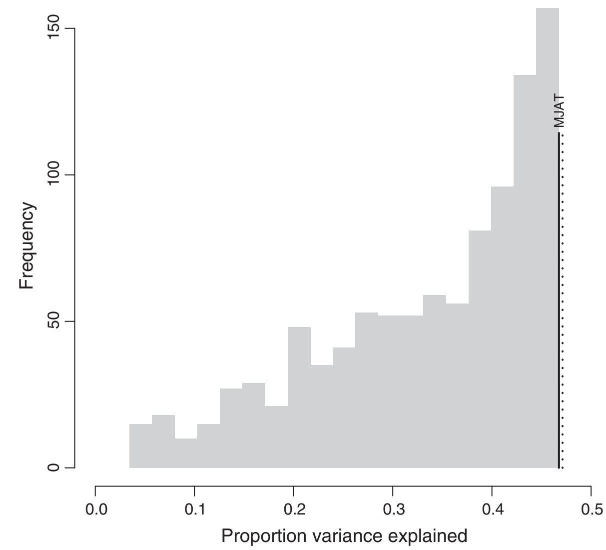

Figure 5. The results from the significance test by Telford and Birks (2011). Histogram of the proportion of variance explained by 999 transfer functions trained on random environmental data. The solid line indicates the proportion of variance explained in the fossil record in the MJAT inference model. The dotted line marks the maximum proportion of variance explainable (i.e. axis 1 of the CA of the fossil samples).

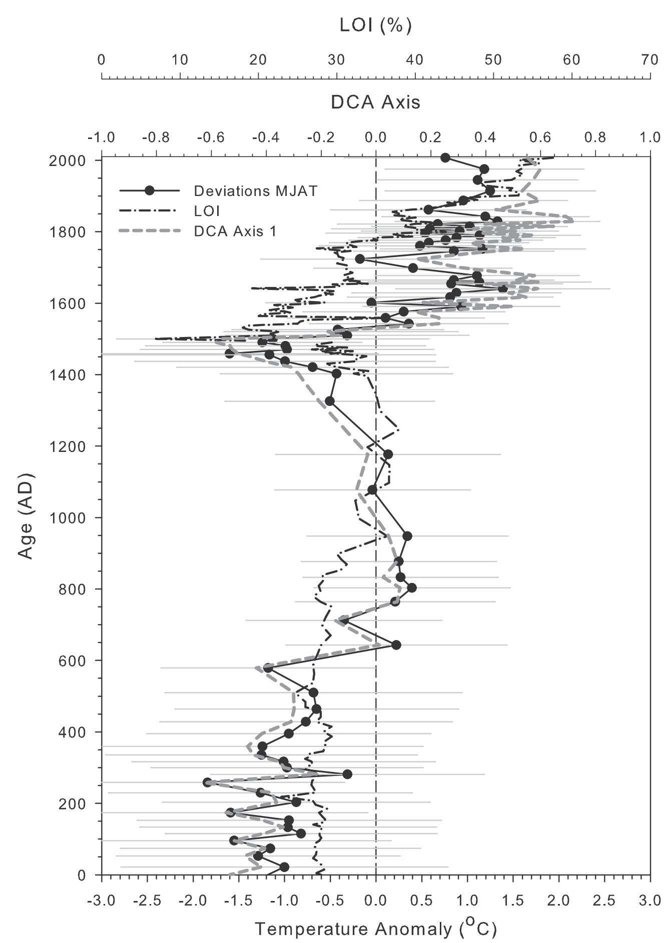

Figure 6. Chironomid-based MJAT anomalies (°C), plotted as deviations from the long-term average MJAT, over the previous two millennia at Stella Lake. Points represent anomalies of chironomid-based MJAT inferences. Error bars indicate the sample-specific error for each sample. The black dash-dot line is LOI. The dashed gray line represents DCA axes 1 scores.

there, their highest levels for the past 2000 yr. Fluctuations in the inferred MJAT around an elevated and relatively stable mean value characterized the remainder of the record. The reconstructed MJAT temperature range captured by variations in the midge community in Stella Lake during the last 2000 yr was 3.0°C (9.4–12.4°C).

Discussion

The midge stratigraphy and results from the DCA indicate that the midge community in Stella Lake underwent major shifts in community composition during the last two millennia. DCA axis 1 identifies the existence of a strong correspondence between the midge community composition and the MJAT estimates (Fig. 6). DCA axis 2 (not shown), with the exception of the interval between AD 800 and AD 1600, is aligned to lake productivity (as estimated by LOI). The ordination results indicate that the midge community is primarily responding to changes in air temperature, with lake productivity a secondary influence.

The most prominent change in the midge stratigraphy of Stella Lake is a dramatic reorganization of the midge community between AD 600 and AD 1600. The portion of the record between AD 600 and AD 1300 was characterized by a large and rapid increase in *P. semicirculatus*/*sordidellus* and *Pentaneurini*. These taxa have relatively high MJAT optima in the Intermountain West training set (Porinchu et al., 2010). The interval between AD 1300 and 1600 was characterized by a rapid faunal turnover, with fluctuations in *C. mancus* group, a taxa with a relatively low MJAT optima in the Intermountain West training set (Porinchu et al., 2010), largely driving the changes observed in the midge community during this interval. The shifts in head capsule concentrations observed in the Stella Lake record likely reflect variations in sedimentation and lake productivity with the elevated concentration of head capsules at the base of the record indicating low sedimentation and high lake productivity (AD 600–1000). The Stella Lake midge community was relatively stable, with limited faunal turnover occurring between AD 0 and AD 500 and AD 1600 to present.

Chironomid-inferred temperatures at Stella Lake reach a core minimum of approximately 1.0°C below the late Holocene average between AD 0 and AD 700. The timing of the depressed MJAT recorded at Stella Lake broadly corresponds to compilations of environmental change from the northern hemisphere indicating that the interval between AD 200 and AD 900 (Fig. 7) was generally characterized by below average temperature (Moberg et al., 2005; Mann et al., 2009; Christiansen and Ljungqvist, 2012; Moinuddin et al., 2013). The timing of the increase in inferred temperatures at Stella Lake, which begins at approximately AD 700, corresponds to the warming documented in Northern Hemisphere reconstructions (Fig. 7) (Moberg et al., 2005; Mann et al., 2009; Christiansen and Ljungqvist, 2012) and pollen-based reconstructions for North America (Moinuddin et al., 2013). More recently a study by Salzer et al. (2014), focusing on tree-ring records, indicated a temperature anomaly of 0.4°C characterized the central Great Basin during the MCA. It is difficult to directly compare the Salzer et al. (2014) reconstruction to our record due to the difference in temporal resolution; however, it is interesting to note that the Salzer et al. (2014) reconstruction indicates that the warming that characterizes the recent century is larger than the inferred warming that occurred during the MCA. A similar pattern exists in the midge-based Stella Lake MJAT reconstruction. The interval between AD 900 and AD 1300, corresponding to the MCA, was distinguished by a local maximum in chironomid-inferred temperatures at Stella Lake of approximately 0.4°C above the late Holocene average, with peak chironomid-inferred MJAT occurring between AD 800 and AD 950. The elevated temperatures which characterize Stella during the late 1st millennium correspond to the warming evidenced

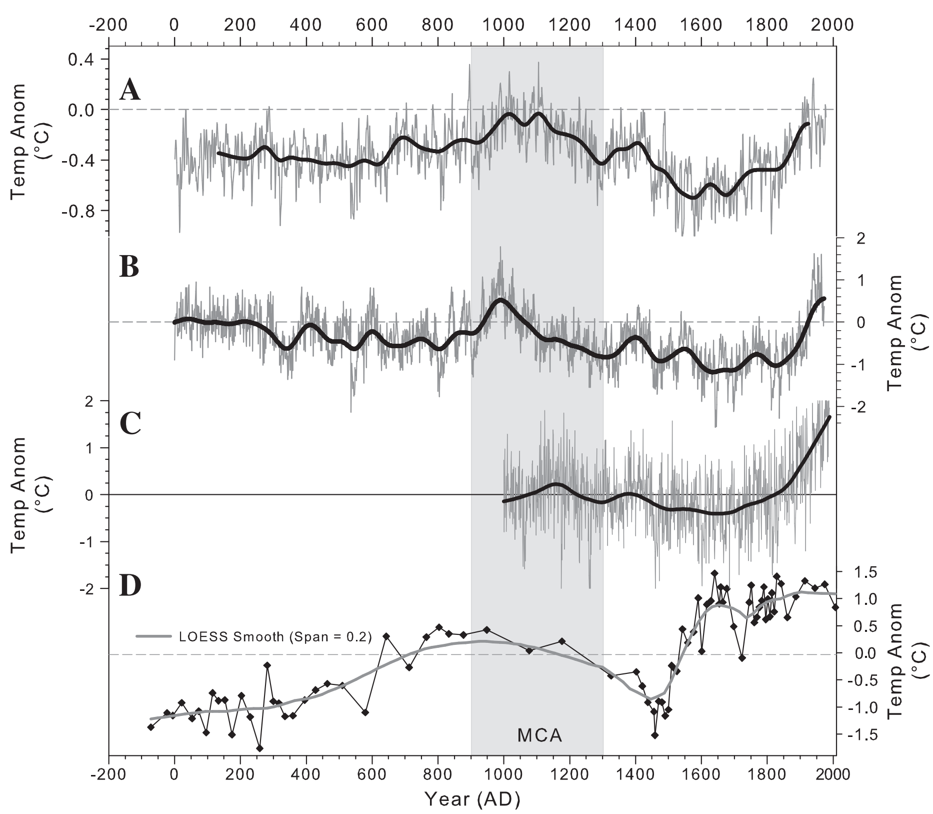

Figure 7. Summary diagram of selected hemispheric and regional temperature reconstructions based on model and paleo-proxy data and data from Stella Lake. (A) Northern Hemisphere mean temperature variations (gray) and its >80-yr component (black) (Moberg et al., 2005), (B) reconstruction of extra-tropical Northern Hemisphere mean temperature variations (gray) and 50-yr smooth (black) (Christiansen and Ljungqvist, 2012), (C) mean temperature deviations from 1000 to 1990 mean of the southwestern United States (box bounded by 40°N, 34°N and 104°W, 124°W) based on ECHO-g forcing 2 model (gray) and loess smooth (span = 0.2) (black) and (D) Stella Lake chironomid-inferred MJAT anomalies (black) and loess smooth (span = 0.2) (gray). Gray shading represents the MCA interval (AD 900–1300).

in the recent pollen-based temperature reconstruction for North America during the same interval (Moinuddin et al., 2013). Near the end of the MCA and extending into the Little Ice Age (LIA) Stella Lake experienced a gradual decrease in MJAT to levels of ~1.0°C below the 2000-yr mean temperature. The drop in temperature documented at Stella Lake corresponds to reconstructed northern hemisphere compilations and regional temperature records, which indicate that decreases in hemispheric and regional temperature began at approximately AD 1000 and continued to AD 1600 (Fig. 7). The lowest temperature during the second millennium occurs at approximately AD 1500 matching the timing of greatest hemispheric temperature anomaly during the last 2000 yr and is associated with a volcanic solar downturn (Moinuddin et al., 2013). The cooling trend observed in Stella Lake between AD 1300 and AD 1600 matches well with the reduced bristle-cone pine ring-widths measured at a number of sites in the Great Basin (Salzer et al., 2009). The depressed temperatures at Stella Lake during the very end of the MCA and beginning of the LIA also correspond to records from the Sierra Nevada that suggest the possible occurrence of a glacial advance during this time interval (Osborn and Bevis, 2001; Bowerman and Clark, 2011). This cold phase was followed by a rapid increase in inferred MJAT beginning at ~AD 1600 and reaching a plateau at ~AD 1800. Chironomid-inferred MJAT increased from ~1.0°C below to ~0.8°C above the long-term average during this interval. The timing of the increase in temperature at Stella Lake appears to closely correspond to the timing of rise in hemispheric temperature, which begins at approximately AD 1600 (Moinuddin et al., 2013). However, the reaching of the recent warming plateau occurs earlier than many other records (Fig. 7). This 'smearing' of the recent warming signal may reflect age model uncertainty at the top of the core with the upper portion of the core not being as well constrained (Fig. 2). It is notable that the recent warming, which exceeds MCA conditions, is in agreement with large-scale reconstructions for the past 1000 to 2000 yrs (Fig. 7; Moberg et al., 2005; Christiansen and Ljungqvist, 2012), Overall, a notable correspondence exists between the Stella Lake MJAT reconstruction over the last two millennia to regional and hemispheric compilations of temperature change (Moberg et al., 2005; Mann et al., 2008; Stevens et al., 2008; Moinuddin et al., 2013). This is true not only in timing of the MCA and LIA, but also in the 0.5°C to 1.0°C amplitude of temperature diversions observed at Stella Lake and these other reconstructions.

Confirmatory evidence for elevated temperature during the MCA is scarce for the Great Basin. The main focus of previous paleoclimate research in this region centered on mapping the spatial extent of the MCA mega-droughts and the magnitude of the reduction in effective moisture and river discharge associated with these mega-droughts. These earlier studies, based on lake-level reconstructions (Graham and Hughes, 2007), vegetation (Mensing et al., 2008), and tree-rings (Cook et al., 2010; Knight et al., 2010; Routson et al., 2011) identify the occurrence of significant hydroclimate fluctuations during the MCA in the western United States (Fig. 8). In addition, Salzer et al. (2009) observed a slight increase in ring widths between AD 900 and AD 1200 and interpreted this increase in ring width as reflective of warmer growing season temperatures (Fig. 8). However, the chironomid-inferred warming of approximately 0.8°C during the MCA at Stella Lake provides quantitative evidence that this region was characterized by elevated temperatures during the MCA. The magnitude of the chironomid-inferred warming at Stella Lake is consistent with model simulations of regional thermal conditions during the MCA. The ECHO-g general circulation model (GCM) (Stevens et al., 2008) indicates that average annual temperatures for the Intermountain West and Nevada reached a maximum of 0.6°C greater than the late Holocene average at AD 1100 and then decrease to −0.6°C below the long-term average until approximately AD 1600. These ECHO-g values compare favorably to the 0.4°C above average MJAT evident in the Stella Lake during the early MCA and the 1.0°C depression in MJAT by AD 1600.

It has been well established that the MCA in the western United States is characterized by two intervals of increased aridity, associated

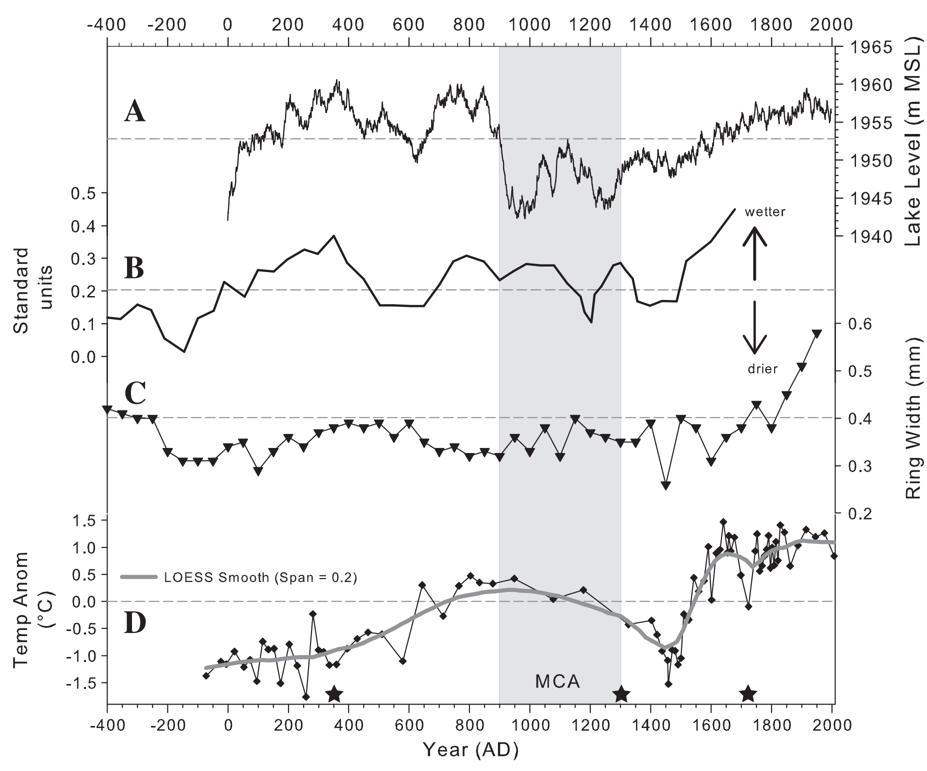

Figure 8. Summary diagram of selected regional paleoclimate records and data from Stella Lake.,(A) Mono Lake level reconstructions (Graham and Hughes, 2007), (B) pollen *Artemisia*/*Chenopodiaceae* (A/C) ratio from Pyramid Lake (Mensing et al., 2008), (C) Bristlecone ring-widths (50 yr median) (Salzer et al., 2009), and (D) Stella Lake chironomid-inferred MJAT anomalies (black line) and loess smooth (span = 0.2) (gray line). Stars indicate glacial advances in the central Sierra Nevada as indicated by Bowerman and Clark (2011). Gray shading represents the MCA interval (AD 900–1300).

with the MCA mega-droughts (Cook et al., 2010). The enhanced aridity has been linked to trends in the Pacific (Seager et al., 2007b; Diaz et al., 2011) and variations in the strength of the NAM (Poore et al., 2005; Asmerom et al., 2007). The MCA mega-droughts have also been associated with the negative phase of the Pacific Decadal Oscillation (PDO) (MacDonald and Case, 2005) and depressed sea-surface temperatures in the eastern Pacific Ocean (Barron et al., 2010). During the MCA, if the interaction between the PDO and the El-Niño Southern Oscillation (ENSO) (Wise, 2010) was similar to modern, a negative PDO accompanied by a more La Niña-like state in the tropical Pacific (Seager et al., 2007b) would facilitate the development of severe droughts in the Great Basin and the southwestern United States. A weaker NAM and lower eastern Pacific SSTs would lead to decreased precipitation and cloud cover and higher temperatures, which in turn could enhance aridity and result in the recorded MCA mega-droughts (Seager et al., 2008; Koster et al., 2009). Conditions in the tropical Pacific would have increased the susceptibility of the Great Basin to severe drought, and may have overridden any influence temperature would have intensified aridity (Seager et al., 2007b).

Current instrumental data shows that high temperatures play a critical role in exacerbating drought in the Great Basin, by influencing effective moisture in a non-linear fashion (Weiss et al., 2009; Shinker and Bartlein, 2010; Weiss et al., 2012). Specifically, Weiss et al. (2009) demonstrated that the droughts of the 1950s and 2000s were associated with anomalously high temperatures. Mock (1996) and more recently Wise (2012) illustrate that modern precipitation, and therefore drought, conditions in the western United States are heavily influenced by large-scale circulations in the atmosphere and ocean. However, the importance of studying smaller-scale processes is also noted because the controls on the western United States climate are variable, highly complex and operate on variable spatial scales (Weiss et al., 2012; Wise, 2012). This highlights the need to further refine our understanding of the role of changing thermal conditions on Great Basin hydroclimatology. For example, paleoclimate records from the region suggest that there have been instances when arid intervals in the Great Basin were associated with below average temperatures (Thompson et al., 1993). However, other regional records (Stevens et al., 2008; Salzer et al., 2009) and the Stella Lake reconstruction presented in this study further support the conclusion that the mega-droughts that characterized this region during MCA occurred during an interval of warmer than average temperature (Woodhouse et al., 2010).

Conclusions

This quantitative sub-centennial chironomid-based temperature reconstruction from Stella Lake provides much need temperature proxy covering the last two millennia in the central Great Basin, a region with very few records. The Stella Lake record establishes that 1) the MCA in the Great Basin was characterized by a notable fluctuation in thermal conditions, 2) the iconic mega-droughts of Medieval times occurred during intervals of above average MJAT, 3) the subsequent Little Ice Age was not only moister, but also cooler, and 4) recent warming may have exceeded MCA conditions. The results of this study support using the MCA as a potential analogue for future scenarios in which elevated temperature is expected to contribute to exacerbating and intensifying aridity in the arid and semi-arid Intermountain West of the United States during the 21st century (Seager et al., 2007a). As conditions in the 21st century have been exceptionally warm and dry in the Great Basin and Southwest (MacDonald, 2010), the paleoclimatic records here and elsewhere suggest continued, and perhaps increased aridity are within the realm of possibility future scenarios for the Great Basin (MacDonald, 2010; Woodhouse et al., 2010). Identifying the role played by temperature in intensifying the aridity associated with the Medieval droughts and earlier drought intervals must be an area of active of research (Woodhouse et al., 2010; Routson et al., 2011) and further documentation of the temperature-aridity relationship will improve our ability to describe and model future hydroclimate variability in the Great Basin and assist in planning for the sustainable use of freshwater resources in the Great Basin.

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