Holocene Climate and Environmental Change in the Great Basin of the Western United States: A Paleolimnological Approach

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

Scott Alan Reinemann, M.S.
Graduate Program in Atmospheric Science

The Ohio State University
2013

Dissertation Committee:
Dr. Bryan G. Mark, Co-Advisor
Dr. David F. Porinchu, Co-Advisor
Dr. Ellen Mosley-Thompson
Dr. Alvaro Montenegro
Abstract

In this dissertation, I have completed a research project that focused on reconstructing past climate and environmental conditions in the Great Basin of the western United States. This research project incorporates four discrete but interrelated studies. (1) The geochemistry of lake sediments was used to identify anthropogenic factors influencing aquatic ecosystems of sub-alpine lakes in the western United States during the past century. Sediment cores were recovered from six high elevation lakes in the central Great Basin of the United States. Mercury (Hg) flux varied among lakes but all exhibited increasing fluxes during the mid-20th century and declining fluxes during the late 20th century. Peak Spheroidal Carbonaceous Particles (SCP) flux for all lakes occurred at approximately 1970, after which SCP flux was greatly reduced. Atmospheric deposition is the primary source of Hg and anthropogenically produced SCPs to these pristine high elevation lakes during the late 20th century. (2) Chironomids are used to develop centennial length temperature reconstructions for six sub-alpine and alpine lakes in the central Great Basin of the United States. Chironomid-inferred temperature estimates indicate that four of the six lakes were characterized by above average air temperatures during the post-AD 1980 interval and below average temperatures during the early 20th century. This study adds to the growing body of evidence that sub-alpine and alpine lakes in the western United States have been, and are increasingly being
affected by anthropogenic climate change in the early 21\textsuperscript{st} century. (3) 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. The chironomid-based mean July air temperature (MJAT) reconstruction suggests that 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. The Stella Lake record provides evidence that elevated summer temperature contributed to the increased aridity that characterized the western United States during the MCA. (4) Lake sediment cores spanning roughly the last 7,000 years were recovered from four small sub-alpine and alpine lakes located in central Great Basin of the United States. Reconstructions of MJAT were developed for each of the study sites using a chironomid-based inference model for MJAT (two-component Weighted Averaging-Partial Least Squares (WA-PLS)). The elevated temperature that characterizes the mid-Holocene at Stella Lake is surpassed only during the Medieval Climate Anomaly and in the post-AD 1800 interval. The reconstructions for the sites located in the northern portion of the study transect are characterized by greater variability, likely reflecting the influence of both radiative forcing and catchment-specific conditions.
Acknowledgments

This dissertation would not have been possible without the professional assistance from my advisors, David Porinchu and Bryan Mark, and my committee members, Berry Lyons, Lonnie Thompson, Alvaro Montenegro, and Ellen Mosley-Thompson. Furthermore I would like to thank family, friends, and colleagues for support through this process. Particularly; all the undergraduate researchers who accompanied me into the field to conduct research; Jim DeGrand for his invaluable help in the lab and in the field; Mike Davis and Meng-Pai Hung for the monthly lunches, to decompress and discuss personal and professional matters; and lastly Gretchen Baker for her help in conducting field work in the Great Basin National Park. The National Science Foundation, the Western National Park Association, and the Department of Geography at The Ohio State University provided financial support. Last, but certainly not the least, I owe my most sincere and heartfelt thanks to my loving wife Christine Reinemann, without her this whole journey and research project would not have been possible.
Vita

January 9, 1984 .............................................. Born

June 2002 .................................................... Waynesville High School

2006 .............................................................. B.A. Meteorology, Ohio University

2008 .............................................................. M.S. Atmospheric Science, Ohio State University

2008 to present .............................................. Graduate Teaching Associate, Department of Geography, The Ohio State University

Publications


A multi-proxy paleolimnological reconstruction of Holocene climate conditions in the

Fields of Study

Major Field: Atmospheric Sciences
# Table of Contents

Vita ........................................................................................................................................... v

List of Tables ................................................................................................................................... xiii

List of Figures ................................................................................................................................... xv

Introduction ........................................................................................................................................ 1

1 Chapter 1: Historical trends of mercury and spheroidal carbonaceous particle deposition in sub-alpine lakes in the Great Basin, United States. ............................................ 10

1.1 Abstract ........................................................................................................................................ 10

1.2 Introduction ..................................................................................................................................... 11

1.3 Study Area ....................................................................................................................................... 14

1.3.1 Lake site descriptions .................................................................................................................... 15

1.4 Materials and methods ..................................................................................................................... 17

1.4.1 Field ............................................................................................................................................ 17

1.4.2 Laboratory .................................................................................................................................... 18

1.5 Results ............................................................................................................................................ 19

1.5.1 Core chronologies ....................................................................................................................... 20
1.5.2 Loss-on-ignition
1.5.3 Mercury concentrations and fluxes
1.5.4 Spheroidal Carbonaceous Particle (SCP) fluxes
1.6 Discussion
1.7 Conclusion
1.8 Acknowledgements
1.9 References
1.10 Tables
1.11 Figures

2 Chapter 2: Regional climate change evidenced by recent shifts in chironomid community composition in sub-alpine and alpine lakes in the Great Basin of the United States

2.1 Abstract
2.2 Introduction
2.3 Study Location
2.4 Methods
  2.4.1 Field
  2.4.2 Laboratory
  2.4.3 Statistics, model development and application
2.5 Results ........................................................................................................................................... 54
2.5.1 Core chronologies .................................................................................................................... 54
2.5.2 Loss-on-ignition ....................................................................................................................... 54
2.5.3 Midge percentage diagrams .................................................................................................... 55
2.5.4 Ordination analyses ................................................................................................................ 59
2.5.5 Chironomid-based temperature reconstructions ................................................................. 59
2.6 Discussion .................................................................................................................................... 61
2.7 Acknowledgements .................................................................................................................... 68
2.8 References .................................................................................................................................... 70
2.9 Table ............................................................................................................................................ 78
2.10 Figures ........................................................................................................................................ 79

3 Chapter 3: A 2000 year reconstruction of air temperature in the Great Basin of the United States with specific reference to the medieval climatic anomaly ......................... 87
3.1 Abstract ....................................................................................................................................... 87
3.2 Introduction .................................................................................................................................. 88
3.3 Study Region ............................................................................................................................ 90
3.3.1 Study Site .............................................................................................................................. 91
3.4 Material and Methods .............................................................................................................. 91
3.5 Results ....................................................................................................................................... 94

ix
3.5.1 Chronology and loss-on-ignition ................................................................. 94
3.5.2 Chironomid Community Change ............................................................... 95
3.5.3 Chironomid-based MJAT reconstruction ................................................... 96
3.6 Discussion .................................................................................................... 97
3.7 Conclusion ................................................................................................. 103
3.8 Acknowledgements .................................................................................... 104
3.9 References .................................................................................................. 106
3.10 Table .......................................................................................................... 113
3.11 Figures ....................................................................................................... 114

4 Chapter 4: A regional synthesis of climate change during the Holocene from the central Great Basin............................................................... 121
4.1 Abstract ..................................................................................................... 121
4.2 Introduction ............................................................................................... 122
4.3 Study Area ............................................................................................... 126
4.4 Methods ..................................................................................................... 127
4.4.1 Sediment Recovery ................................................................................ 127
4.4.2 Laboratory Analyses and Chronological Control .................................... 127
4.4.3 Chironomid Analysis ............................................................................ 128
4.4.4 Statistical Analyses .............................................................................. 129
Chapter 1 ...................................................................................................................... 177
Chapter 2 ...................................................................................................................... 183
Chapter 3 ...................................................................................................................... 190
Chapter 4 ...................................................................................................................... 197
Conclusion ..................................................................................................................... 203
List of Tables

Table 1.1 Selected limnological and environmental measurements for the study sites.
SWT = Surface Water Temperatures. *Sensor malfunction.............................................. 36

Table 1.2 Hg flux values and flux ratios of all six sediment cores. S.D. = Standard Deviation. Pre-industrial (pre-1880 AD) and modern (post-1985). Those values without standard deviation are taken from a single sample. The average flux ratio is computed for all NV lakes, and published average flux ratios from the Eastern and Western U.S. are listed for comparison........................................................................................................ 37

Table 1.3 Mercury modern/preindustrial flux ratios from sediment cores in North American lakes. Adapted from Mast et al. (2010)............................................................... 38

Table 2.1 Selected limnological and environmental measurements for the study sites.
*Sensor malfunction. ........................................................................................................ 78

Table 3.1 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. .............................................................................. 113
Table 4.1 AMS $^{14}$C dates used to derive age-depth models for the study sites. The National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) (Woods Hole, Massachusetts), and Beta Analytic Inc. (Miami, Florida) provided the dates. Lab code refers to NOSAMS sample number (OS-) or the Beta Analytic sample number (Beta-). ................................................................. 156

Table 4.2 Geographic co-ordinates, year of coring, total core length, the number of levels examined for chironomids, the mean number of chironomid head capsules (he) identified from each chironomid level and additional limnological characteristics for each of the study sites.......................................................... 157
List of Figures

Figure 1.1 Location of study site lakes located in the Great Basin of the western United States. Six lakes, marked by an “X” are located within the East Humboldt Range, Ruby Mountains and Great Basin National Park (GBNP) (boundary plotted on map). Large cities and major lakes plotted as reference. Counties in the State of Nevada are identified. .............................................................................................................................................................................................................................................................................................................39

Figure 1.2 Radiometric chronologies of Smith, Birdeye, Teresa, Dead, Cold, and Stella lakes based on $^{210}$Pb, depicting the constant rate of supply (CRS) model dates and sedimentation rates. SE = standard error. *Note the different vertical axis for depth and sedimentation rates.............................................................................................................................................................................................................................................................................................................40

Figure 1.3 SEM image of SCPs taken from selected lakes. (A) Cold Lake - 6.0 cm depth and (B) Teresa Lake - 4.0 cm depth. Note the different magnification represented by the scale bars.............................................................................................................................................................................................................................................................................................................................................................................................................................................................................................................................................................................................................................................41

Figure 1.4 Loss-on-Ignition conducted at 550°C from Cold (black circle), Stella (grey downward triangle), Dead (grey square), Teresa (grey diamond), Birdeye (grey upward triangle), and Smith (light grey circle) lakes graphed with respect to time.............................................42

Figure 1.5 Mercury accumulation rate (or flux) (grey triangle) and SCP flux (black circle) from all six lakes. Open triangle denotes interpolated age by mean sedimentation rate. *Note the difference in x-axis scales for Total Hg & SCP Flux.............................................43
Figure 1.6 A summary diagram of regional records of total mercury concentrations and accumulation rate (or flux) and the lakes in this study. (a) Fremont ice core total Hg concentrations (Schuster et al. 2002), (b) mean concentrations of total Hg from lakes in this study, (c) total Hg flux from lakes in this study, (d) total Hg flux six lakes in the WACAP report (Landers et al. 2008) (SEKI= Sequoia and Kings Canyon N.P., MORA=Mount Rainier N.P., ROMO=Rocky Mountain N.P.).

Figure 2.1 Location of study site lakes in the Great Basin of western United States (inset). The six lakes are located within the East Humboldt, Ruby Mountains and Great Basin National Park (boundary plotted on map). Nevada counties and major lakes are labeled for reference.

Figure 2.2 Radiometric chronologies for Smith, Birdeye, Teresa, Dead, Cold and Stella lakes depicting the constant rate of supply model and sedimentation rates. Note the different vertical axes for depth and sedimentation rates.

Figure 2.3 Loss-on-Ignition (%) conducted at 550°C from Cold (black circle), Stella (grey downward triangle), Dead (grey square), Teresa (grey diamond), Birdeye (grey upward triangle), and Smith (light grey circle) lakes graphed with respect to time.

Figure 2.4a – c. Chironomid stratigraphies for Smith (a), Birdeye (b), Cold (c), Stella (d), Teresa (e), and Dead (f) lakes. The order is based on the lakes’ location from north to south (matching Fig. 7). Taxa have been arranged according to their MJAT optima from the chironomid-based inference model, with decreasing optima temperature from left to right. Horizontal lines divide chrono zones, as identified in the text. Abbreviations for
chironomid taxa: *Psectrocladius semi*/sordi-type = *Psectrocladius semicirculatus*/sordidellus*. (continued).................................82

Figure 2.5 DCA Axis 1 plotted against age for Smith, Birdeye, Teresa, Dead, Cold and Stella lakes. Heavy dashed lines represent a LOWESS smoother (span = 0.40).............84

Figure 2.6 Chironomid-based mean July air temperature reconstructions for Smith, Birdeye, Teresa, Dead, Cold and Stella lakes. Points represent chironomid-based MJAT inferences, with positive SSE plotted in light gray. The dotted line is the average chironomid inferred temperature for the entire interval of each lake. The heavy dashed line represents a LOWESS smoother (span = 0.40). .....................................................85

Figure 2.7 Deviations of the chironomid-based MJAT from the long term mean of each lake ordered based on the lakes’ location (Fig. 1) from north (Smith Lake) to south (Dead Lake). Deviations of air temperature over the period AD 1895-2012 for Nevada Climate Division #2, which encompasses all the lake sites. Thick line represents a LOWESS smoother (span = 0.4). .................................................................86

Figure 3.1 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)........................................................................................................114

Figure 3.2 Age-depth model for the sediment core from Stella Lake (grey), overlaying the calibrated distributions of individual dates (blue). Grey dotes indicate the model’s 95% probability intervals as outputted by *bacon* routine (Blaauw and Christen, 2011). The
upper left inset show 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).

Figure 3.3 Chironomid relative abundance diagram for Stella Lake. Taxa have been arranged according to their MJAT optima from the midge-based inference model, with decreasing optima temperature from left to right. *Psectrocladius semi/sordid*-type = *Psectrocladius semicirculatus/sordidellus*.

Figure 3.4 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 3.5 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 grey line represents DCA axes 1 scores.

Figure 3.6 Summary diagram of select hemispheric and regional temperature reconstructions based on model and paleo-proxy data and data from Stella Lake. (a) Northern Hemisphere mean temperature variations (grey) and its >80-yr component (black) (Moberg et al., 2005), (b) Reconstruction of extra-tropical Northern Hemisphere
mean temperature variations (grey) and 50-yr smooth (black) (Christiansen and Ljungqvist, 2012), (c) mean temperature deviations from 1000-1990 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 (grey) and loess smooth (span = 0.2) (black) and (d) Stella Lake chironomid-inferred MJAT (black) and loess smooth (span = 0.2) (grey). Gray shading represents the MCA interval (AD 900 – 1300).

Figure 3.7 Summary diagram of select 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 year median) (Salzer et al., 2009), and (d) Stella Lake chironomid-inferred MJAT (black line) and loess smooth (span = 0.2) (grey line). Gray shading represents the MCA interval (AD 900 – 1300).

Figure 4.1 Location of study sites located in the Great Basin of western United States. The study sites are located in the East Humboldt Mountains, the Ruby Mountains or the Snake Range of Nevada. Large cities, major lakes and the boundary of Great Basin National Park is plotted for reference.

Figure 4.2 Age-depth model for the sediment cores from all lakes (grey), overlaying the calibrated distributions of individual dates (blue). Grey dots indicate the model’s 95% probability intervals as provided by the BACON routine (Blaauw and Christen, 2011).

Figure 4.3 Loss-on-Ignition (thin line) conducted at 550°C for (A) Angel Lake, (B) Soldier Lake, (C) Overland Lake, and (D) Stella Lake graphed with respect to age. LOESS smooth (thick line) with a span = 0.2.
Figure 4.4a–d Chironomid stratigraphies for Angel (a), Soldier (b), Overland (c), and (d) Stella lakes, the order is based on the lakes’ location from north to south. Taxa have been arranged according to their MJAT optima from the chironomid-based inference model, with decreasing optima temperature from left to right. Abbreviations for chironomid taxa: *Psectrocladius semi/sordi*-type = *Psectrocladius semicirculatus/sordidellus*. (continued) .......................................................... 161

Figure 4.5 DCA Axis 1 plotted against age for Angel (a), Soldier (b), Overland (c), and (d) Stella lakes. Heavy solid lines represent a LOWESS smoother (span = 0.20). ........ 166

Figure 4.6 Chironomid-based mean July air temperature reconstructions for Angel (a), Soldier (b), Overland (c), and (d) Stella lakes. Points represent chironomid-based MJAT inferences, with positive SSE plotted in light gray. The heavy line represents a LOWESS smoother (span = 0.20). .......................................................... 167

Figure 4.7 Deviations of the chironomid-based MJAT from the long term mean of Angel (a), Soldier (b), Overland (c), and (d) Stella lakes, ordered based on the lakes’ location from north to south. Thick line represents a LOWESS smoother (span = 0.20). ........ 168

Figure 4.8 Bathymetric map of Soldier Lake.......................................................... 169

Figure 4.9 Summary diagram of select published paleoclimate records from all lakes in this study. (a) LOESS smooth of the chironomid-inferred MJAT anomaly relative to the AD 1000 – AD 2000 year MJAT average (b) Chironomid DCA axis 1 , (c) Loss-on-ignition, (d) North American pollen-based July air temperature anomaly (Viau et al., 2006), (d) pollen A/C ratio from Pyramid Lake (Mensing et al., 2004), and (e) Insolation changes at 30°N (Berger and Loutre, 1991). .......................................................... 170
Introduction

With the increasing recognition that high-elevation and high-latitude regions are both responsive and extremely sensitive to changes in temperature and precipitation, it is critical that we improve our understanding of how global climate change will affect freshwater resources and aquatic ecosystems in sub-alpine and alpine environments (Bradley et al., 2004; Parker et al., 2008). This is especially true given the heightened concern over present and future water availability in mountainous environments, such as those that characterize much of the Intermountain West of the United States. Improving our knowledge of the characteristics and behavior of aquatic ecosystems in alpine environments is vital for predicting future water availability and secondary ecological responses to climate change. This will not only strengthen our ability to develop meaningful scenarios describing the potential future response of these freshwater systems to projected global change but also improve our ability to manage these natural systems and the freshwater water resources they contain (Adrian et al., 2009; Schindler, 2009).

Alpine ecosystems in the Great Basin are poorly monitored, with only limited faunal surveys and long-term instrumental climate data available. However, paleolimnology, which focuses on extracting information preserved in lake sediment records, is well positioned to identify and assess the effects of anthropogenic climate change. Lakes act as sentinels due to their ability to integrate local and regional signals of
climate and environmental change (Smol and Douglas, 2007; Smol, 2008). Paleolimnology focuses on extracting information preserved in lake sediment records, providing a broad time perspective on changes in aquatic ecosystem structure and composition that can help to identify the direct and indirect effects of climate and environmental change on aquatic ecosystems (Williamson et al., 2008; Adrian et al., 2009; Mladenov et al., 2011). A paleolimnological approach can be used to study the modern distribution of aquatic fauna in high elevation lakes and establish ‘baseline’ conditions against which the effects of projected warming in these regions can be evaluated (Camarero and Catalan, 2012). In addition, paleolimnology can be used to assess how the biotic and abiotic components of aquatic ecosystems have responded to anthropogenic and natural forcings, such as altered thermal regimes, pollutant loading and land use change (Fenn et al., 2003; Holzapfel and Vinebrooke, 2005; Parker et al., 2008; Murphy et al., 2010). It is important to note that the recent changes in biota, nutrients, and geochemical cycles that have been identified in western North America are linked to both natural and anthropogenic climate change (Karst-Riddoch et al., 2005; Parker et al., 2008).

Chironomids, also known as non-biting midges, possess a number of characteristics that make them well-suited for use as a biological proxy for paleoecological and paleoclimate studies (Porinchu and MacDonald, 2003; Eggermont and Heiri, 2012). One, they have relatively short life cycles. Two, adult midges have the ability to disperse in search of more favorable environmental conditions and habitat. Three, they are sensitive to key environmental variables such as temperature, oxygen
concentration, and lake depth. Lastly, the larval remains are abundant and well preserved in lake sediment. For these reasons chironomids have now been used for over 20 years to quantify the changing thermal conditions of lakes, starting most notably with Walker et al. (1991). The utility of sub-fossil midge analysis in paleoclimate research, which has been recognized beyond the paleolimnological community, has resulted in development of hundreds of quantitative midge-based temperature reconstructions over the last two decades (Eggermont and Heiri, 2012), the majority of which are from the mid- to high northern latitudes. More recently, the large number of well-constrained Holocene temperature reconstructions from the Northern Hemisphere has enabled researchers to critically assess the reliability of millennial and centennial-scale midge-based estimates of past temperature and to examine the potential influence of confounding factors on these quantitative reconstructions (Velle et al., 2010, 2012; Brooks et al., 2012).

In this dissertation, I have completed a research project that focused on reconstructing past climate and environmental conditions in the Great Basin of the western United States. This research project incorporates four discrete but interrelated studies. These studies are centered on: (1) investigating the influence of pollutant loading on high elevation sub-alpine and alpine lakes during the 20th and 21st centuries; (2) documenting the response of sub-alpine and alpine lakes in the central Great Basin to recent anthropogenic climate change; (3) developing a detailed, multi-decadal resolution, quantitative reconstruction of thermal conditions for Stella Lake in Great Basin National Park (GBNP) spanning the last two millennia; and (4) developing a regional chironomid-based synthesis of Holocene environmental and climate change for the central Great
Basin. The dissertation thus consists of four chapters that detail the study sites, methods, results and discussion for each of the research foci.

A note on the organization of the dissertation; Chapters 1-4 of the dissertation are written as independent papers, for which I am the principal author. My advisors, David Porinchu and Bryan Mark, are co-authors because they played a critical role in the design of the research and contributed to the interpretation of the results presented in these chapters. M.S. Gustin is a co-author of Chapter 1 because she conducted much of the laboratory analyses and contributed greatly to the interpretation and writing of the paper. G.M. MacDonald and J.Q. DeGrand are co-authors on Chapter 3 because they contributed substantially during the fieldwork, laboratory analyses, and the writing of the paper. J.S. Munroe is a co-author for chapter 4 because he contributed the sediment cores for two of the lakes in the study and has helped with the interpretation of the records. The dissertation then concludes with a brief discussion of the major findings. References for all works cited within a chapter are located at the end of the respective chapter. Below is a brief introduction to each chapter.

In the first chapter, I investigate historical changes in the deposition of spheroidal carbonaceous particles (SCP) and mercury (Hg) to remote alpine and sub-alpine lakes in the central Great Basin of the western United States. Using Hg, SCPs, and sediment organic content (Loss-on-Ignition (LOI)), I examine $^{210}$Pb-dated sediment cores collected from six lakes in the Ruby Mountains and the East Humboldt and Snake ranges of Nevada. A version of this chapter entitled “Historical trends of mercury and spheroidal carbonaceous particle deposition in sub-alpine lakes in the Great Basin, United States”,
co-authored with D.F. Porinchu, M.S. Gustin, and B.G. Mark, has been submitted to *Journal of Paleolimnology*.

In the second chapter, I make use of sediment cores from six lakes, dated using $^{210}$Pb, and analyzed for sediment organic content (LOI) and sub-fossil midges to document the response of sub-alpine and alpine lakes in the central Great Basin to recent climate change. I also use detrended correspondence analysis (DCA) to evaluate the timing and magnitude of compositional turnover in these lakes. In addition, I apply a chironomid-based MJAT inference model (Porinchu et al., 2010) to develop high-resolution MJAT reconstructions spanning the 20th and 21st centuries for this region. A version of this chapter entitled “Regional Climate Change Evidenced by Recent Shifts in Chironomid Community Composition in Sub-alpine and Alpine Lakes in the Great Basin of the United States”, co-authored with D.F. Porinchu and B.G. Mark, has been submitted to *Arctic, Antarctic, and Alpine Research*.

In the third chapter, I apply the chironomid-based inference model for MJAT (Porinchu et al., 2010) and develop a detailed, multi-decadal scale, quantitative reconstruction of thermal conditions for Stella Lake in Great Basin National Park (GBNP) that spans the last two millennia. I also use LOI to make qualitative inferences of lake productivity. This study expands on my earlier work describing Holocene Thermal Maximum (HTM) conditions in Great Basin National Park (GBNP) (Reinemann et al., 2009) and provides a much needed, well-constrained (multi-decadal resolution), paleotemperature record for the Great Basin spanning the last 2000 years. This quantitative reconstruction will improve our understanding of the temporal patterns of
past climate change during the Medieval Climate Anomaly (MCA), an interval characterized by significant regional hydroclimate variability (Cook et al., 2004; MacDonald, 2007; Mensing et al., 2008; Conroy et al., 2009; Woodhouse et al., 2010; Routson et al., 2011). A version of this chapter entitled “A 2000 Year Reconstruction of Air Temperature in the Great Basin of the United States with Specific Reference to the Medieval Climatic Anomaly”, co-authored with D.F. Porinchu, G.M MacDonald, B.G. Mark, and J.Q. DeGrand, has been submitted to *Quaternary Research*.

In the final chapter, I investigate the changing thermal and environmental conditions at four sub-alpine to alpine lakes in the central Great Basin over the mid- to late-Holocene, with specific reference to the Holocene Thermal Maximum (HTM). The lake cores have been chronologically constrained using $^{14}$C dates to provide robust chronologies covering the length of this investigation. I used DCA to evaluate the timing and magnitude of compositional turnover in the lakes. Lastly, we applied a chironomid-based MJAT inference model (Porinchu et al., 2010) to develop MJAT reconstructions spanning the mid- to late-Holocene for central Nevada. The results from this study indicate the need for careful site selection when reconstructing Holocene temperatures. A version of this chapter entitled “A Chironomid-based Synthesis of Mid- to Late-Holocene Environmental Change in the Central Great Basin, of the Western United States.”, co-authored with D.F. Porinchu, B.G. Mark, and J.S. Munroe, will be submitted to *Palaeogeography, Palaeoclimatology, Palaeoecology*. 


Chapter 1: Historical trends of mercury and spheroidal carbonaceous particle
deposition in sub-alpine lakes in the Great Basin, United States.

1.1 Abstract

The geochemistry of lake sediments was used to identify anthropogenic factors
influencing aquatic ecosystems of sub-alpine lakes in the western United States during
the past century. Sediment cores were recovered from six high elevation lakes in the
central Great Basin of the United States. The proxies utilized to examine the degree of
recent anthropogenic environmental change include spheroidal carbonaceous particles
(SCP), mercury (Hg) and sediment organic content estimated using loss-on-ignition
(LOI). Chronologies for the sediment cores, developed using \(^{210}\)Pb, indicate the cores
span the 20\(^{th}\) century. Hg flux varied between lakes but all exhibited increasing fluxes
during the mid-20\(^{th}\) century and declining fluxes during the late 20\(^{th}\) century. The mean
ratio of modern (post-A.D. 1985) to preindustrial (pre-A.D. 1880) Hg flux was 5.2, which
is comparable to the results from previous studies conducted in western North America.
Peak SCP flux for all lakes occurred at approximately 1970, after which the SCP flux was
greatly reduced. Based on Hg concentrations and calculated sedimentation rates
atmospheric Hg flux increased in the early 1900s, from 1970 to 1990, and is currently
increasing. This is suggested to reflect local, regional and global inputs, respectively.
Atmospheric deposition is the primary source of Hg and anthropogenically produced SCPs to these pristine high elevation lakes in the Great Basin during the late 20th century.

1.2 Introduction

Human-induced alterations to the biochemical cycle have impacted the National Parks, National Forests, and Wilderness Areas in the western U.S. and will continue to impact them into the future (Wolfe et al. 2003; Porter and Johnson 2007; Neff et al. 2008). A multi-institution, multi-agency study, the Western Airborne Contaminant Assessment Project (WACAP), recently assessed the impacts of pollutant loadings to National Parks in the western United States (Landers et al. 2010). The WACAP’s objectives were four-fold: 1) determine if contaminants were present and if so, where they were accumulating; 2) determine which contaminants could be used to monitor anthropogenic influence; 3) identify which contaminants were an ecological threat; and 4) determine the most likely source(s) of pollution to the sites (Landers et al. 2008). One of the key findings from the lake sediment-based analyses incorporated in WACAP is that the concentration of most contaminants peaked in the late 20th century before subsequently declining in response to the Clean Air Act and its amendments (Landers et al. 2008). The WACAP report determined that the regional influence of agricultural and industrial areas was of more importance to the pollution deposition than the global transport from outside the region (Landers et al. 2008). The study highlighted the importance of further documenting the role of pollutants on influencing aquatic and terrestrial function and composition, and suggested that expanding the spatial extent of
the original study would be required to assess the representativeness of the results and conclusion presented in the final WACAP report (Landers et al. 2010).

The fate of mercury (Hg) in aquatic systems is of great interest. Mercury belongs to a class of toxins that persists in aquatic environments and bioaccumulates in food chains (Selin 2009). Many studies have documented historical changes in Hg concentration and flux in lakes sediment cores throughout North America (Engstrom et al. 1994; Fitzgerald et al. 1998; Kamman and Engstrom 2002; Drevnick et al. 2010; Mast et al. 2010; Phillips et al. 2011). Early research on assessing the impact of Hg on aquatic systems focused primarily on the midwestern and eastern U.S. as the centers of Hg production and therefore contamination (Lorey and Driscoll 1999; Engstrom et al. 2007). However, it has become increasingly recognized that Hg input to aquatic ecosystems in the western U.S. should not be ignored (Landers et al. 2008; Mast et al. 2010). This is particularly important because sub-alpine and alpine lakes may be more susceptible to increased deposition of Hg due to the higher concentrations of reactive gaseous mercury (RGM) at higher elevation (Swartzendruber et al. 2006; Huang and Gustin 2012).

Spheroidal carbonaceous particles (SCPs), comprised mostly of elemental carbon, are produced during high temperature combustion of fossil fuels due to incomplete combustion of the coal or fuel-oil (Rose 2008). SCPs are not produced by the burning of wood, biomass, or charcoal and thus, have no natural sources (Rose 1994). SCPs are in the 5 to 50 μm range and can be transported between 1,000 km and 2,000 km from their source (Rose 2001). SCPs are mostly used as a direct measurement of anthropogenic contamination through space (multiple site comparison) and time (single site, down core)
SCP input to lakes have been correlated with the deposition of various heavy metals, including Hg (Rose 2001), providing a means to attribute metal deposition in the lake sediments to specific sources and trajectories. For example, atmospheric transportation and deposition are implicated when the records of both heavy metal and SCP concentration show strong temporal coherence. In contrast, a high concentration of heavy metals associated with a low SCP concentration indicates that the source of heavy metals is likely located within the catchment and related to local geology (Rose 2001). The solely anthropogenic source of SCPs and the simplicity of extracting SCPs from the sediment matrix make them an invaluable tool in paleolimnology for documenting the onset and degree of human influence.

This study focused on investigating historical changes in the deposition of SCPs and Hg to remote alpine and sub-alpine lakes in the central Great Basin of the western United States. Mercury (Hg), SCPs, and sediment organic content (estimated using loss-on-ignition (LOI)) are examined in $^{210}\text{Pb}$-dated sediment cores collected from six lakes in the Ruby Mountains, and the East Humboldt and Snake ranges of Nevada. The lakes were chosen as part of a larger, on-going climate/paleoclimate research project; however, these lakes are excellent candidates to fill the gap in spatial coverage in the central Great Basin identified in the WACAP report. This study thus provides: a regional baseline for atmospheric contaminant loading; it can be used to identify the degree to which aquatic ecosystems in these vulnerable regions have been impacted by anthropogenic activities.
(Wolfe et al. 2003; Karst-Riddoch et al. 2005), and provides a broader temporal context against which future changes in aquatic ecosystem structure and function can be evaluated (Smol 2008; Schindler 2009).

1.3 Study Area

The study sites are located in central and eastern Nevada within the Great Basin of the United States. Specifically, the lakes lie in the East Humboldt Range, Ruby Mountains and Snake Range (Figure 1.1). The Great Basin is internally drained, and characterized by horst and graben topography with north-south trending mountains and valleys (Eaton 1982). The dramatic relief of the Great Basin greatly influences local climate, with steep temperature and precipitation gradients associated with elevation. The valley floors experience summer (June, July, Aug.) mean temperatures of 22°C and winter (Dec, Jan, Feb) mean temperatures of -1°C, while high elevations are characterized by summer mean temperatures of 13.5°C and winter mean temperatures of -7°C. Precipitation occurs primarily in the winter and early spring (dominated by snowfall), with lesser amounts in the summer associated with convective thunderstorms (WRCC 2012). The average annual precipitation varies between 20 to 31 centimeters, with smaller amounts in the south and larger amounts in the north (WRCC 2012). Prevailing winds generally come from the northwest, west, or southwest, however the region may also experience a consistent southerly wind due to the influence of summertime high pressure in the western United States (Houghton et al. 1975).
1.3.1 Lake site descriptions

Smith Lake (41° 2'2.11"N, 115° 5'37.23"W; 2781 m a.s.l.) is located on the northeastern side of the East Humboldt Range. It is surrounded by sparse patches of Pinus flexilis (limber pine) and Populus tremuloides (quaking aspen). This lake has inlet and outlet streams. The inlet stream is primarily spring fed, and together with groundwater inputs and surface runoff, sustain the lake. The lake is underlain by glacial moraine (Coats 1987). The upper reaches of the catchment including the headwall consist of metamorphic rock formations comprising granitic to dioritic gneiss, biotite schist, quartzitic schist, schistose quartzite, pegmatite, lime silicate granulite, lime silicate marble, and pure marble (Coats 1987). There are also small formations of Ely Limestone and Pequp Formation (mostly limestone) (Coats 1987). There is no reported mining within the catchment of Smith Lake; however, there was a tungsten mine operating 10 km to the east of the catchment in the late 20th century (Lapointe et al. 1991).

Birdeye Lake (40°54'56.62"N, 115° 9'34.05"W; 2855 m a.s.l.) is located on the west side of the East Humboldt Range. It is surrounded by sparse patches of pines (P. flexilis) and low lying shrubs of. It lies along a ridgeline extending westward from Humboldt Peak on the main divide of the East Humboldt Range. Based on the small catchment size, lack of influent stream and location, this lake is completely sustained by either snowmelt and/or groundwater inputs. The lake is underlain by metamorphic rocks of the same material that surround Smith Lake. There is no record of mining within the catchment (Lapointe et al. 1991).
Cold Lake (40°42'52.65"N, 115°18'6.85"W) is located in the northern part of the Ruby Mountains. The vegetation surrounding the lake is composed of *P. flexilis*, *Salix spp.* (willow), and alpine meadow plants. Cold Lake occupies a north-facing cirque on the west side of the mountain range close to the headwall of the valley. It has a small inlet stream, primarily spring fed, and an outlet stream. These keep the lake level relatively constant. Snowmelt, groundwater and/or surface runoff also contribute to water in this lake. At the time of coring in August 2011, there were still two large snow fields extending to the edge of the lake. Cold Lake is underlain by foliated metaquartzite, consisting mostly of quartz, feldspar and mica. Cold Lake’s catchment includes some calcite marble in the headwall (Coats 1987). There is no history of mining within the catchment (Lapointe et al. 1991).

Stella (39° 0'18.72"N, 114°19'7.42"W), Dead (38°56'8.71"N, 114°16'27.23"W) and Teresa (39° 0'11.37"N, 114°18'40.68"W) lakes are located in Great Basin National Park (GBNP) along the northeastern side of the Snake Range. Stella and Dead lakes are fed only from groundwater, snowmelt, and/or surface runoff, with no active inlet or outlet streams. Dead Lake’s extremely small size and catchment area may make it susceptible to drying out during extreme droughts. Teresa Lake has an inlet stream that is spring fed and no outflow stream, so the lake must also be fed by a groundwater system. Stella and Teresa lakes are underlain by quartzite of Precambrian and Cambrian age, with late Quaternary glacial till present at the surface and are damned by glacial moraines (Rollin et al. 1976). Pioche Shale, Prospect Mountain Quartzite, and the McCoy Creek Group comprise the Stella Lake and Teresa Lake catchments (Rollin et al. 1976). Dead Lake is
underlain by intrusive rock composed of monzonite and granodiorite (Rollin et al. 1976); however, from personal observation the lake is situated on a large Quaternary glacial moraine. A large mining project consisting of several large gold and gold placer mines existed in the Osceola District of White Pine County, located in the northeast portion of GBNP. These mines were in operation between A.D. 1902 and A.D. 1959, and produced gold, silver, copper, lead, zinc and tungsten (Rollin et al. 1976). This mining district is on the northwestern side of the Snake Range. For the lakes studied in GBNP only the Dead Lake catchment had a mine located within its boundaries and this was a small tungsten mine (Rollin et al. 1976).

1.4 Materials and methods

1.4.1 Field

Sediment was recovered by a messenger-operated corer modeled after a Glew corer (Glew 1991), to increase the diameter of the core. The cores were collected from the approximate center of the lakes in two different field campaigns during August, 2010 and 2011. The cores varied in diameter with 5 cm diameter cores recovered in 2010 and 7.5 cm diameter cores recovered in 2011. The sediment-water interface of the core was undisturbed during sediment recovery. The sediment cores varied in length from 8 to 27 cm, and all were sectioned in the field at 0.25 cm intervals from 0 to 15 cm, 0.5 cm intervals between 15 to 20 cm, and at 1 cm intervals below 20 cm. The sediment was stored in Whirl-paks®, kept cool and in the dark during transport to the lab at The Ohio State University (OSU). Water temperature, dissolved oxygen, salinity, pH, conductivity,
and specific conductivity were measured at the time of sediment collection using a YSI 556 multi-meter. During sediment collection, measurement of Secchi depth and maximum lake depth were also made from the coring location (see Table 1.1).

1.4.2 Laboratory

To develop chronological control, 12 sediment samples from each lake core were analyzed for $^{210}$Pb activity using $\alpha$-spectroscopy (Figure 1.2). The sampling interval used to constrain the chronologies increased with depth and ranged from 0.25 to 2.0 cm. This increasing sampling interval is used to capture the exponential decay of unsupported $^{210}$Pb in the longer sediment cores. Ages and sedimentation rates (g cm$^{-2}$ yr$^{-1}$) were calculated using a constant rate of supply (CRS) model; for equations on how these are calculated the readers are directed to Appleby (2001). The CRS model is appropriate in environments where sediment accumulation rates change with depth (Turner and Delorme 1996). The $^{210}$Pb analysis was carried out by MyCore Scientific Incorporated (Dunrobin, Ontario, Canada). For depths below which a reliable $^{210}$Pb age could be estimated, the mean sedimentation rate was used to extrapolate the chronology to the base of the cores. There is a large degree of uncertainty in extrapolating the chronology to the base of the cores. To estimate the amount of organic carbon present in the lake sediment and obtain an estimate of overall lake productivity, loss-on-ignition (LOI) at 550°C, was determined at a 0.5 cm resolution (Heiri et al. 2001).

Analyses of the lake sediments for SCPs followed procedures outlined in Rose (1994). Dried sediments were digested in sequential acid baths of nitric acid (HNO$_3$), hydrofluoric acid (HF), and hydrochloric acid (HCl) in polytetrafluoroethylene (PTFE)
tubes, that removed organic, siliceous, and carbonate material, respectively. A measured fraction of the remaining suspension was dried on a cover slip and permanently mounted on a slide using either Naphrax® or Entellan® for preservation and identification. The SCPs where then identified and counted using a light microscope at 400x magnification. A select set of samples were identified under a scanning election microscope to positively identify the presence of SCPs (Figure 1.3). The abundance of SCPs were converted to a concentration, i.e. SCPs per gram of dry mass or gDM⁻¹ (Rose 1994).

Total Hg content in the freeze dried sediments was determined using a Milestone™ Direct Mercury Analyzer (Model DMA 80, AMA 254 Software). Analyses of standard reference materials (NIST 2702, NIST 2709) were used to ensure that the instrument calibration was within 5%. Every 12 samples, standards were analyzed to check for instrument drift. Samples at each depth interval were analyzed in triplicate and the mean value was reported. The total Hg concentrations are reported in nanograms of Hg per gram of dry mass (ng g⁻¹). Flux of total Hg through time was calculated by multiplication of the concentration and the sedimentation rate from each sample and is reported as micrograms per meter squared per year (µg m⁻² yr⁻¹). Flux ratios were determined as the ratio of modern to preindustrial flux of total Hg (Table 1.2). The modern values represent the mean values for the most recently deposited sediment analyzed for each lake post A.D. 1985. The preindustrial values are single or mean values prior to A.D. 1880.

1.5 Results
1.5.1 Core chronologies

Profiles of the $^{210}$Pb age to depth relationship, along with sedimentation rates are presented in Figure 1.2. The depth at which supported $^{210}$Pb reaches background values varies among the lakes (Smith – 8 cm; Birdeye – 9 cm; Cold – 10 cm; Stella – 21 cm; Dead – 6.5 cm; Teresa – 5.5 cm), with the well-constrained section of each record spanning the following intervals: Smith Lake (A.D. 2010–1905), Birdeye Lake (A.D. 2010–1935), Cold Lake (A.D. 2011–1900), Stella Lake (A.D. 2011–1900), Dead Lake (A.D. 2010–1905), and Teresa Lake (A.D. 2010–1915) (Figure 1.2). Comparison of sedimentation rates among lakes for the well-constrained sections identified above yields a coefficient of variation between 2 and 17%. Overall the relatively uniform sedimentation rates and the existence of exponential $^{210}$Pb decay profiles (Figure 1.2) in all cores suggest that these chronologies should be considered reliable.

1.5.2 Loss-on-ignition

The LOI analysis indicates that all six lakes exhibit similar trends in the percent loss-on-ignition (Figure 1.4). The LOI values in all the lakes remained relatively constant through much of the 20th century. The LOI values began to rise at approximately A.D. 1970 at all sites. The increase in LOI in the upper sediment likely reflects the differing degrees of decomposition and sediment composition in the surface sediments and not a large increase in productivity (Dean 1999; Shuman 2003). The catchment area and surface lake area data, presented in Table 1.1, indicate that the study lakes are characterized by relatively small catchment areas, with the exception of Teresa Lake. Stella Lake was the most productive lake with LOI values ranging between 30% and
55%, far exceeding the ranges in the other lakes. The drainage ratio (catchment area: lake surface area) indicates a large difference between Stella Lake (5.7) and the remainder of the lakes (25 to 154). The LOI values for the basal sediment from Cold, Dead, Teresa, Birdeye, and Smith lakes vary between 10% and 20%, increasing to 20 to 40% in the upper sediment. Based on LOI, Cold and Smith lakes were the least productive of the lakes with LOI values fluctuating around 10% through much of the 20th century.

1.5.3 Mercury concentrations and fluxes

The mean concentrations and standard deviations for Hg for the lakes are: Smith Lake 132 ng/g ±12; Birdeye Lake 122 ng/g ±11; Cold Lake 125.9 ng/g ±20.5; Stella Lake 116.3 ng/g ±9.8; Teresa Lake 90.7 ng/g ±4.9 and; Dead Lake 121.4 ng/g ±14.2. The Hg flux for each lake is shown in Figure 1.5. Five lake cores display broadly similar patterns in Hg flux, with an initial increase in the late 19th-early 20th century and a secondary peak in the late 20th century. There is also an increase from ~2010 to the present observed for five out of the six cores. The mean modern: pre-industrial flux ratio for the six Great Basin lakes was 5.2 ± 3.9 (Table 1.2).

There are site-specific differences in Hg flux. For example, there is a notable Hg flux peak between A.D. 1890 and A.D. 1925 in the Birdeye, Smith, Teresa, Dead and Stella lake core sediments but not in Cold Lake. In contrast, Cold Lake shows a gradual increase in Hg flux rates through the early 20th century, with a peak occurring at approximately A.D. 1975 before decreasing during the late 20th century, and ultimately increasing in the uppermost samples. Stella, Dead, and Teresa lakes are small lakes located on the eastern side of the Snake Range in GBNP and exhibit similar trends in Hg
These lakes feature a peak in Hg flux during the early 20th century, then a marked decrease after approximately A.D. 1970 followed by a slight increase in the most recent sediments. The somewhat muted Hg flux in Teresa Lake might be due to a low sedimentation rate.

1.5.4 Spheroidal Carbonaceous Particle (SCP) fluxes

The results of the SCP analysis reveal that the study sites are also characterized by a broadly similar temporal pattern in SCP flux, with some site-specific differences (Figure 1.5). All six lakes exhibited a peak in SCP flux to the sediment between A.D. 1950 and A.D. 1975, followed by a greatly reduced flux in the post-1980 interval. The SCP flux in the northern study lakes (i.e. Birdeye, Cold and Smith lakes) peaks between A.D. 1960 and A.D. 1970. Within GBNP there is a similar pattern in the SCP flux for Teresa and Dead lakes, with a peak occurring at approximately A.D. 1970, whereas, Stella Lake features a broader peak in SCP flux that begins earlier (~A.D. 1950).

1.6 Discussion

In any lake-based study, local, regional and global sources of Hg need to be evaluated in order to determine if the fluctuations in the observed Hg flux in any given lake sediment record is due to changes in atmospheric contaminant loading rather than alterations in catchment input. For example, the existence of a “Mercury Belt” in eastern Nevada (Gray et al. 1999) could potentially lead to a natural enrichment in Hg locally. However, careful examination of the geologic setting of the lakes reveals that the changes in Hg flux apparent in the sedimentary records are not likely to be driven by local Hg inputs derived
from the respective lake catchments. The bedrock geology of the lakes incorporated in this study are not located in areas typically characterized by elevated Hg concentrations and therefore, are unlikely to influence Hg input to the study lakes (Rollin et al. 1976; Coats 1987). Another possible source of Hg contamination in this particular region of the western United States is point source pollution from active or historical mines and associated mining activities. Bulletins from the Nevada Bureau of Mines and Geology indicate that there are no known mines or prospects within the catchments of the six lakes that could contribute Hg to the lakes through direct runoff (Rollin et al. 1976; Lapointe et al. 1991). It is important to note that a group of large mines were active in the Osceola District in northeastern GBNP between A.D. 1902 and A.D. 1959. However, not only was the use of Hg leaching limited at the Osceola mine, but the mines associated with the Osceola district are not located in the catchment of the studied lakes (Rollin et al. 1976). The lack of a local source of Hg strongly suggests that the increased Hg flux in the early and late 20th century evidenced at the study sites is due to regional and/or global atmospheric deposition of Hg to the lake surface and surrounding catchment.

The similarities in Hg fluxes in all the study sites indicate spatial and temporal correspondence over the East Humboldt, Ruby Mountains and GBNP regions. The early peak between A.D. 1890 and A.D. 1925 recorded in five of the six lakes (Smith, Birdeye, Stella, Teresa and Dead) (Figure 1.5) post-dates the major gold mining activities of the late 1800’s. However, remobilization of mercury in soils and subsequent downwind dispersal could account for the lag in timing between the initial mining activity and Hg
deposition (Nriagu 1994). The uncertainty inherent in the basal portion of the $^{210}\text{Pb}$ chronologies for the individual records could also account for this apparent inconsistency.

The Hg flux of all the lakes is consistent with regional studies of ice cores (Schuster et al. 2002) and lake sediments (Heyvaert et al. 2000; Landers et al. 2008; Mast et al. 2010) (Figure 1.6). These studies document increasing Hg fluxes in the mid-20th century and a marked decline following the early 1970’s, similar to the Hg fluxes in Smith, Birdeye, and Stella lakes which exhibit a secondary peak at A.D. 1970. The Cold Lake Hg flux does not exhibit a pre-1980 record that is similar to the ice core record. This is possibly due to its location as the most northern lake in this study. Cold and Stella lakes are the only sites with samples extending beyond approximately A.D. 2005 and it is in these two lakes that we see a pronounced increase in Hg in the most recently deposited sediments (Figure 1.6). The mean modern flux of total Hg to the sediments (40 μg m$^{-2}$ yr$^{-1}$) in the six lakes of our study is also similar to values reported in other studies from across a large region of the western U.S. A core taken by Heyvaert et al. (2000) in Lake Tahoe was reported to feature a modern Hg flux of 47 μg m$^{-2}$ yr$^{-1}$. At Glacier and Rocky Mountain National Parks, Mast et al. (2010) report an average modern flux from nine lakes of 46 μg m$^{-2}$ yr$^{-1}$; the average flux drops to 35 μg m$^{-2}$ yr$^{-1}$ if data from a problematic lake is removed. This study further supports the assertion that the modern flux of Hg to high elevation lakes is strikingly similar across a large area of the western U.S.

A notable difference between this study and previous research is the existence of a slight increase in Hg flux in all the study lakes in the uppermost sediments. This
increase could result from one or a combination of three factors: 1) increased productivity and associated algal scavenging of Hg from the water column in the upper most unconsolidated sediment (Outridge et al. 2007); 2) recent increases in gold mining activities upwind of the lake sites since Hg is a by-product of the mining process (Eckley et al. 2011); and 3) increased releases of Hg due to industrialization in Asia (Pirrone and Mason 2009). The first of these hypotheses involving increased primary productivity and associated algal scavenging of Hg (Outridge et al. 2007) is not supported by the LOI results of this study. Although factors other than with-in lake productivity can influence LOI values, LOI can be used to provide estimates of primary productivity (Meyers and Ishiwatari 1993). It is still important to note that LOI can be influenced by: (1) sediment composition through changes of lake productivity (autochthonous inputs) and catchment conditions (allochthonous inputs) and; (2) sediment accumulation through changes in basin morphology and water level. Therefore, LOI values reported from a single core must be interpreted with caution (Shuman 2003). LOI begins to rise prior to the increase in Hg flux in during the late 1990’s and LOI does not appear co-vary with Hg during the early 20th century (Figures 4 & 5).

The modern to preindustrial mean Hg flux ratio in the six lakes ranged from 1.1 to 9.5 with a mean value of 5.2. These values are comparable to other remote lakes from the western United States and elsewhere in North America (Table 1.3). Although, the Hg flux ratios of the Great Basin lakes are within the range found in other studies from the western U.S the flux ratios are characterized by notable inter-lake variability. The lakes in this study with greatest flux ratios (Cold, Smith, Dead) have values between 7.5 and
9.5, which are somewhat higher than those that have been documented in Colorado, Montana and Wyoming (Van Metre and Fuller 2009; Mast et al. 2010), but within the range of those found at high elevation sites California (Heyvaert et al. 2000; Sanders et al. 2008). Cold and Smith lakes may possibly be responding to a recent increase in local Hg input from the existence of large open-pit gold mines, opened in the late 1980s, just upwind from the lakes in the Carlin Trend (Ressel and Henry 2006). The lakes with lowest flux ratios (Stella, Birdeye, Teresa) are located on the downwind side of a ridge and may experience topographic sheltering due to their location. Nevertheless, the mean flux ratios calculated in this study are in broad agreement with previous studies that have identified the existence of a 3-5X enrichment in the modern:pre-industrial Hg in lake sediments from remote areas in North America (Lorey and Driscoll 1999; Mast et al. 2010).

The second aspect of this study involved examining whether remote lakes in the central Great Basin have been influenced by anthropogenic atmospheric pollution as evidenced by the presence of SCPs (Figure 1.5). The SCP flux record for all six lakes demonstrates a marked decline post-1970. The decline is most likely the result of stronger particulate controls on coal fired power plants and the switch to natural gas at some facilities after the implementation of the Clean Air Act (1970) and its amendment (1990) (CCA 1990; Landers et al. 2010). Similar SCP flux records exist for two groups of lakes (Birdeye & Cold and Smith, Teresa, & Dead). The Stella Lake SCP flux is not similar to the other GBNP lakes. The lack of correspondence between the Stella Lake record and the other GBNP lakes could be due to a number of factors including lake size, elevation
and aspect, proximity of SCP sources, and influence and direction of prevailing winds. These factors have all been identified as influencing the magnitude of SCP input to lakes (Rose 2001). A possible explanation for the discrepancy between the SCP records may involve the proximity of the individual lakes to SCP sources or the sheltering effect related to the proximity of the lakes to the head wall of the catchment on the leeward or windward side of their respective mountain ranges.

The SCP flux records developed in this study suggest that late 20th century contaminant loadings, e.g. Hg, originated largely via atmospheric deposition for most of the late 20th century, because of the wholly anthropogenic source(s) of SCPs. However the records of Hg and SCP deposition do exhibit within-lake variability. This difference could reflect differing sources for both pollutants. In general, sources of Hg are found at all spatial scales (local, regional and global), and SCPs are more likely associated with regional and local sources (Yang and Rose 2003; Gustin et al. 2008; Landers et al. 2010). Differential dispersal and sources for Hg and SCPs, respectively may account for the observation of decreasing SCP fluxes and steady or increasing Hg fluxes in the uppermost sediment samples.

There is a growing body of evidence from Europe and the United States connecting recent decreases in SCP fluxes to the more efficient removal of particulates from power station flue gases as a result of the regulations implemented following the passage of the Clean Air Act (1970) and its amendment (1990) (Rose and Monteith 2005; Landers et al. 2010). For example, the SCP flux evidenced in the uppermost sediment of the study lakes in the Ruby Mountains and the East Humboldt Range do not reflect the
presence of nearby coal-fired power plants which came on-line in the early 1980’s and are located directly upwind of the sites. The results of this study, which demonstrates that lakes in the central Great Basin experienced a general decrease in pollutant loadings post-1970, match the results of the WACAP report, which identified the peak flux of SCP as occurring circa the late 1960s. This study further substantiates the results of the WACAP study by documenting the representativeness of the WACAP study for outlining the timing and magnitude of atmospheric contaminant/pollution of lakes in the western U.S. Identifying the temporal and spatial variability of Hg and other pollutant fluxes is essential given the capacity of these pollutants to accumulate in aquatic environments and damage ecosystem health (Watras et al. 1994).

1.7 Conclusion

The results of this study demonstrate that remote aquatic ecosystems in the central Great Basin have been affected by local, regional, and global anthropogenic pollutant loading over the 20th century, in this order. SCPs, which varied in absolute concentration among the study lakes, nevertheless provide a consistent signal of increasing pollution loadings to the study sites in the late 20th century, followed by a subsequent decline, likely resulting from stricter pollution controls within the United States and Europe. Mercury fluxes exhibit a slightly more complex regional signal. Two of the study sites were characterized by peak Hg flux during the early 1970s, while the Hg flux at the remaining sites peaked in the early 20th century. All the lakes exhibit a slight increase in the Hg and SCP flux in the most recently deposited sediment. Recent work has suggested inputs from the free troposphere that could be derived regionally or globally (Huang and Gustin
2012). To further understand what may be driving this recent increase in the Hg flux to the sediment, more work is need to describe the transport of Hg and track pollution sources.

1.8 Acknowledgements

We thank Gretchen Baker (Staff Ecologist, GBNP), Andrew J. Ferguson (Superintendent, GBNP) and United States Forest Service (USFS) for providing access to the research sites and facilitating our research. We also thank Paul Soltesz, Jim DeGrand, Nate Patrick for their unyielding assistance in the field; and Christian Briggs and Lydia Peri for analyzing Hg in the sediment samples at University Nevada-Reno. The scanning electron microscope images of the SCPs presented in this report were generated using the instruments and services at the Campus Microscopy and Imaging Facility, The Ohio State University. We gratefully acknowledge The Western National Park Association (WPNA), the Department of Geography at The Ohio State University, and a NSF Doctoral Dissertation Improvement Grant to D. F. Porinchu and S.A. Reinemann (BCS-1130340) for funding this research.
1.9 References


Landers DH, Simonich SL, Jaffé DA, Geiser LH, Campbell DH, Schwindt AR, Schreck CB, Kent ML, Hafner WD, Taylor HE, Hageman KJ, Usenko S, Ackerman LK,


### 1.10 Tables

<table>
<thead>
<tr>
<th>Variables</th>
<th>Smith Lake</th>
<th>Birdeye Lake</th>
<th>Cold Lake</th>
<th>Stella Lake</th>
<th>Teresa Lake</th>
<th>Dead Lake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year Cored</td>
<td>2010</td>
<td>2010</td>
<td>2011</td>
<td>2011</td>
<td>2010</td>
<td>2010</td>
</tr>
<tr>
<td>Elevation (m a.s.l.)</td>
<td>2780</td>
<td>2854</td>
<td>3015</td>
<td>3175</td>
<td>3135</td>
<td>2916</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>3.6</td>
<td>3.85</td>
<td>6.0</td>
<td>1.5</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Surface Area (ha)</td>
<td>1.8</td>
<td>0.6</td>
<td>0.4</td>
<td>3.0</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>Catchment Area (ha)</td>
<td>63.9</td>
<td>15.2</td>
<td>40.5</td>
<td>17.0</td>
<td>107.9</td>
<td>5.2</td>
</tr>
<tr>
<td>Drainage Ratio (catchment:lake surface)</td>
<td>33.6</td>
<td>25.3</td>
<td>101.3</td>
<td>5.7</td>
<td>154.1</td>
<td>52.0</td>
</tr>
<tr>
<td>Secchi Depth (m)</td>
<td>Unlimited</td>
<td>Unlimited</td>
<td>5.12</td>
<td>Unlimited</td>
<td>Unlimited</td>
<td>Unlimited</td>
</tr>
<tr>
<td>Measured SWT (°C)</td>
<td>15.09</td>
<td>17.05</td>
<td>10.07</td>
<td>13.77</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

Table 1.1 Selected limnological and environmental measurements for the study sites. SWT = Surface Water Temperatures. *Sensor malfunction
<table>
<thead>
<tr>
<th>Lake</th>
<th>Hg flux (μg m(^{-2}) yr(^{-1}))</th>
<th>Modern (Post- A.D. 1985)</th>
<th>Preindustrial (Pre- A.D. 1880)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smith</td>
<td>25.3 ± 0.7 S.D.</td>
<td>2.7</td>
<td></td>
<td>9.5</td>
</tr>
<tr>
<td>Birdeye</td>
<td>21.6 ± 3.0 S.D.</td>
<td>8.7</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>Cold</td>
<td>96.4 ± 20.3 S.D.</td>
<td>11.0</td>
<td></td>
<td>8.8</td>
</tr>
<tr>
<td>Stella</td>
<td>57.5 ± 9.2 S.D.</td>
<td>38.0 ± 7.4 S.D.</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>Teresa</td>
<td>8.2 ± 1.3 S.D.</td>
<td>7.5 ± .5 S.D.</td>
<td></td>
<td>1.1</td>
</tr>
<tr>
<td>Dead</td>
<td>35.4 ± 1.5 S.D.</td>
<td>4.7 ± 0.6 S.D.</td>
<td></td>
<td>7.5</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>5.2</td>
</tr>
<tr>
<td>Average of Mast et al. (2010)</td>
<td>Western U.S.</td>
<td>3.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.2 Hg flux values and flux ratios of all six sediment cores. S.D. = Standard Deviation. Pre-industrial (pre-1880 AD) and modern (post-1985). Those values without standard deviation are taken from a single sample. The average flux ratio is computed for all NV lakes, and published average flux ratios from the Eastern and Western U.S. are listed for comparison.
<table>
<thead>
<tr>
<th>Location</th>
<th>Range</th>
<th>No. of sites</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vermont/New Hampshire</td>
<td>2.1-6.9</td>
<td>10</td>
<td>(Kamman and Engstrom 2002)</td>
</tr>
<tr>
<td>New York</td>
<td>1.6-5.7</td>
<td>8</td>
<td>(Lorey and Driscoll 1999)</td>
</tr>
<tr>
<td>Ontario</td>
<td>2.2-2.3</td>
<td>3</td>
<td>(Lockhart et al. 1998)</td>
</tr>
<tr>
<td>Alberta</td>
<td>0.4-2.8</td>
<td>9</td>
<td>(Phillips et al. 2011)</td>
</tr>
<tr>
<td>Minnesota</td>
<td>3.2-4.9</td>
<td>7</td>
<td>(Swain et al. 1992)</td>
</tr>
<tr>
<td>Minnesota</td>
<td>2.0-5.7</td>
<td>5</td>
<td>(Wiener et al. 2006)</td>
</tr>
<tr>
<td>Colorado/Montana</td>
<td>2.9-3.6</td>
<td>9</td>
<td>(Mast et al. 2010)</td>
</tr>
<tr>
<td>Wyoming</td>
<td>4.6-6.5</td>
<td>2</td>
<td>(Van Metre and Fuller 2009)</td>
</tr>
<tr>
<td>Nevada</td>
<td>1.1-9.5</td>
<td>6</td>
<td>This study</td>
</tr>
<tr>
<td>California</td>
<td>9.5-18.7</td>
<td>3</td>
<td>(Heyvaert et al. 2000)</td>
</tr>
<tr>
<td>California</td>
<td>3.3-10.8</td>
<td>4</td>
<td>(Sanders et al. 2008)</td>
</tr>
</tbody>
</table>

Table 1.3 Mercury modern/preindustrial flux ratios from sediment cores in North American lakes. Adapted from Mast et al. (2010).
Figure 1.1 Location of study site lakes located in the Great Basin of the western United States. Six lakes, marked by an “X” are located within the East Humboldt Range, Ruby Mountains and Great Basin National Park (GBNP)(boundary plotted on map). Large cities and major lakes plotted as reference. Counties in the State of Nevada are identified.
Figure 1.2 Radiometric chronologies of Smith, Birdeye, Teresa, Dead, Cold, and Stella lakes based on $^{210}\text{Pb}$, depicting the constant rate of supply (CRS) model dates and sedimentation rates. SE = standard error. *Note the different vertical axis for depth and sedimentation rates.
Figure 1.3 SEM image of SCPs taken from selected lakes. (A) Cold Lake - 6.0 cm depth and (B) Teresa Lake - 4.0 cm depth. Note the different magnification represented by the scale bars.
Figure 1.4 Loss-on-Ignition conducted at 550°C from Cold (black circle), Stella (grey downward triangle), Dead (grey square), Teresa (grey diamond), Birdeye (grey upward triangle), and Smith (light grey circle) lakes graphed with respect to time.
Figure 1.5 Mercury accumulation rate (or flux) (grey triangle) and SCP flux (black circle) from all six lakes. Open triangle denotes interpolated age by mean sedimentation rate.

*Note the difference in x-axis scales for Total Hg & SCP Flux.*
Figure 1.6 A summary diagram of regional records of total mercury concentrations and accumulation rate (or flux) and the lakes in this study. (a) Fremont ice core total Hg concentrations (Schuster et al. 2002), (b) mean concentrations of total Hg from lakes in this study, (c) total Hg flux from lakes in this study, (d) total Hg flux six for lakes in the WACAP report (Landers et al. 2008) (SEKI= Sequoia and Kings Canyon N.P., MORA=Mount Rainier N.P., ROMO=Rocky Mountain N.P.).
Chapter 2: Regional climate change evidenced by recent shifts in chironomid community composition in sub-alpine and alpine lakes in the Great Basin of the United States

2.1 Abstract

Chironomids (non-biting midges) are used to develop centennial length temperature reconstructions for six sub-alpine and alpine lakes in the central Great Basin of the United States. Faunal turnover, assessed by detrended correspondence analysis (DCA), indicate that substantial compositional change in the midge communities has occurred during the last 100 years. Although the changes in compositional turnover are site-specific, increases in *Dicrotendipes* and decreases in *Procladius* characterize the late 20th century at a majority of the sites. Notable faunal turnover in midge community composition is observed at five of the six sites beginning at approximately AD 1970. Application of a chironomid-based mean July air temperature inference model (\(r^2_{\text{jack}} = 0.55\), RMSEP = 0.9°C) to the subfossil chironomid assemblages provides site-specific quantitative reconstructions of past temperature variability for the 20th and 21st centuries. Chironomid-inferred temperature estimates indicate that four of the six lakes were characterized by above average air temperatures during the post-AD 1980 interval and below average temperatures during the early 20th century. The rate of temperature change between AD 1920 and AD 2010 for these four lakes are: Smith Lake = 0.6°C/100 years;
Birdeye Lake = 0.7°C/100 years; Cold Lake = 1.2°C/100 years; Stella Lake = 0.4°C/100 years. Correspondence between fluctuations in the chironomid-inferred temperature and instrumental measures of mean July air temperature for Nevada Climate Division #2 is also documented. This study adds to the growing body of evidence that

2.2 Introduction

The Intermountain West of the United States, home to the fastest growing population in the United States, is increasingly affected by global climate change (Wise, 2012). Much of this region has experienced a severe to exceptional drought, amongst the most severe recorded in the instrumental record, during the late 20th and early 21st centuries (Cook et al., 2004). Observed changes in regional hydroclimatology include decreased snowpack, earlier spring-melt runoff peaks, altered seasonality of precipitation, and a change in the snow to rainfall ratio (Knowles et al., 2006; Westerling et al., 2006; Harpold et al., 2012; Wise, 2012). In the southern portion of the Intermountain West, Williams et al. (2010) assessed the response of vegetation to increasing warmth and aridity and determined that forests in the southwestern United States are on a trajectory towards elevated mortality and will likely be more susceptible to future disturbances. In addition, recent work by Kulakowski et al. (2013) suggests that conifer dominated forests in the western United States will experience reduced regeneration in response to compound disturbances including the direct and indirect effects of climate change. Global climate change has also been implicated in altering alpine aquatic ecosystem structure, composition and function in western North America (Fenn et al., 2003; Wolfe...
et al., 2003; Porter and Johnson, 2007; Baron et al., 2009; Hobbs et al., 2011; Saros et al., 2011).

Lakes act as sentinels due to their ability to integrate local and regional signals of climate and environmental change (Smol and Douglas, 2007; Smol, 2008). Paleolimnology focuses on extracting information preserved in lake sediment records, providing a broad time perspective on changes in aquatic ecosystem structure and composition that can help to identify the direct and indirect effects of climate change (Williamson et al., 2008; Adrian et al., 2009; Mladenov et al., 2011) and pollutant loading (Reinemann et al., n.d.; Baron et al., 2000; Fenn et al., 2003; Sickman et al., 2003; Wolfe et al., 2003; Neff et al., 2008; Saros et al., 2011) on aquatic ecosystems. Paleolimnology provides an effective means to monitor changes in faunal distribution in mountain lakes and establish ‘baseline’ conditions against which the effects of projected warming in these regions can be evaluated (Camarero and Catalan, 2012) and assess how the biotic and abiotic components of aquatic ecosystems have responded to anthropogenic and natural forcings. For example, increased levels of nitrogen deposition and algal productivity have been documented in alpine lakes in the Rocky Mountains (Wolfe et al., 2003). Furthermore, recent work suggests that high elevation lakes in the Intermountain West will be highly susceptible to increasing temperatures, resulting in significant amounts of species turnover in aquatic ecosystems (Holzapfel and Vinebrooke, 2005). It is important to note that the recent changes in biota, nutrients and geochemical cycles that have been identified in western North America are linked to both
natural and anthropogenic climate change (Karst-Riddoch et al., 2005; Parker et al., 2008).

Chironomids, also known as non-biting midges, possess a number of characteristics that make them well-suited as a biological proxy for paleoclimate studies (Porinchu and MacDonald, 2003; Eggermont and Heiri, 2012). One, they have relatively short life cycles. Two, adult midges have the ability to disperse in search of more favorable environmental conditions and habitat. Three, they are sensitive to key environmental variables such as temperature, oxygen concentration and lake depth. Lastly, the larval remains are abundant and well preserved in lake sediment. We are studying chironomid communities in sub-alpine and alpine lakes in the western United States to examine the response of midges to recent observed climate change as recorded by the instrumental record (Porinchu et al., 2007a, 2010). Assessing the degree of correspondence between compositional change and climate observations will increase our confidence in quantitative down-core MJAT reconstructions over longer time scales (centuries to millennia) and allow us to begin to examine how climate change has impacted high elevation aquatic ecosystems in the Great Basin during the recent past.

This paper builds on previous studies that have made use of sub-fossil midge analysis to document the impact of recent natural and anthropogenically induced environmental change on aquatic communities (Porinchu et al., 2007a; Larocque et al., 2009; Larocque-Tobler et al., 2009; Medeiros et al., 2012). Regionally, change in the composition of aquatic ecosystems has been documented in the Sierra Nevada (CA), Snake Range (NV), and Uinta Mountains (UT) (Porinchu et al., 2007a, 2010). These and
other studies have demonstrated that environmental change has greatly affected sub-alpine, alpine and arctic lakes in North America and Eurasia, with aquatic communities experiencing dramatic re-organization in recent decades (Smol et al., 2005; Rühland et al., 2008; Hobbs et al., 2010; Battarbee and Bennion, 2011). The goal of this study is to add to the growing body of evidence documenting the impacts of climate change on alpine and sub-alpine lake ecosystems in the Great Basin of the United States. This is especially important because alpine and sub-alpine lakes in the Great Basin are poorly monitored with limited faunal surveys and long-term instrumental climate data available.

We make use of sediment cores from six lakes, dated using $^{210}$Pb, and analyzed for sediment organic content (estimated by loss-on-ignition (LOI)) and sub-fossil midges to document the response of sub-alpine and alpine lakes in the central Great Basin to recent climate change. The results from this study are compared to existing midge stratigraphies and temperature reconstructions from sites in the Sierra Nevada, CA and the Snake Range, NV (Porinchu et al., 2007a, 2010). The chironomid-inferred MJAT reconstructions are also compared to instrumental records from NOAA Climate Division #2 to assess the robustness of the reconstructions.

2.3 Study Location

The study sites are located in the Great Basin of the western United States (Figure 2.1). The Great Basin is characterized by horst and graben topography. The presence of alternating high mountain ranges and long narrow valleys allow for wide local variations in temperature and precipitation. The mountain ridges experience mean winter
(December, January, February) and summer (June, July, August) temperatures of approximately -7 °C and 13.5 °C, respectively. The valley floors experience mean summer temperatures of 22 °C and mean winter temperatures of -1.0 °C (WRCC, 2012). Overall precipitation, which is limited in the Great Basin due to its location on the lee side of the Sierra Nevada, ranges from approximately 100 mm to 450 mm annually. This produces a semi-arid to arid climate. Precipitation maxima vary from winter to spring over the entire Great Basin, with some areas experiencing a summer maximum due to convective storm activity (WRCC, 2012).

The six lakes are small (<2 ha), and have a mean elevation of 2980 m a.s.l. (see Table 2.1 for details). Smith Lake (41.033920°N, 115.093674°W) is located in the East Humboldt range in central Nevada at an elevation of 2780 m. The lake covers a surface area of 1.75 ha. Birdeye Lake (40.915728°N, 115.159457°W) is located in the East Humboldt range in central Nevada at an elevation of 2850 m. The lake is positioned on the north side of a ridge that extends west from the main divide in the range. The lake has a surface area of 0.60 ha. Cold Lake (40.714761°N, 115.301720°W) is located in the northern Ruby Mountains of central Nevada at an elevation of 2777 m. The lake, which is 0.40 ha, is situated directly below the head of the drainage basin, adjacent to the headwall on the west side of the crest. At the time of coring in August, 2011 snow was located immediately adjacent to the lake. Stella (39.005332°N, 114.318686°W), Dead (38.935738°N, 114.274232°W) and Teresa (39.003244°N, 114.311286°W) lakes are located in the Snake Range of eastern Nevada. They are found at elevations of 3170, m, 2916 m, and 3135 m, respectively. Stella Lake is located in the headwater region of
Lehman Creek and currently does not have a clear inflow or out-flowing stream. Dead Lake is situated on a large Quaternary glacial moraine and its small volume and catchment area likely result in desiccation during extended droughts (pers comm, Gretchen Baker). Teresa Lake, which has the largest drainage area of the six lakes, is fed by a spring-fed inlet stream with no surface outflow. Teresa Lake experiences large fluctuations in lake level, as observed from repeated trips to the lake between 2005 and 2011. The surface area for Stella, Dead and Teresa lakes is 3.0, 0.10 and 0.70 ha, respectively.

2.4 Methods

2.4.1 Field

Sediment was recovered from the approximate center of each lake by a messenger-operated, modified Glew gravity corer. The cores recovered varied in diameter, with 5 cm diameter cores recovered in August 2010 and 7.5 cm diameter cores recovered in August 2011. The corer was deployed from an inflatable raft anchored in the deepest portion of the lake. All cores preserved the flocculent surface sediment, evidenced by little to no disturbance of the surface-water interface. Sediment was extruded in the field at 0.25 cm increments between 0 and 15 cm, 0.5 cm increments between 15 and 20 cm, and at 1.0 cm increments for depths greater than 20 cm. The sediment was stored in Whirl-paks®, and kept cool and dark during transport to the Integrated Paleoenvironmental Laboratory (IPL) at The Ohio State University. At the time of collection, measurements of maximum depth, secchi depth and water temperature
profiles, conductivity, DO and pH (using a YSI multimeter; pH sensor malfunctioned in 2010) were made (see Table 2.1).

2.4.2 Laboratory

The lake productivity was estimated using loss-on-ignition (LOI) analysis following a standard procedure, as outlined by Heiri et al. (2001). LOI analysis was conducted at 0.5 cm resolution for all cores. To develop chronological control, 12 sediment samples from each lake core were analyzed for $^{210}$Pb activity using α-spectroscopy. The sampling interval used to develop the chronologies ranged from 0.25 to 2.0 cm, with the sample interval increasing with depth. An increasing sampling interval is used to capture the exponential decay of unsupported $^{210}$Pb in the longer sediment cores. Ages and sedimentation rates (g cm$^{-2}$ yr$^{-1}$) were calculated using a constant rate of supply (CRS) model Appleby (2001). The CRS model is appropriate in environments where sediment accumulation rates change with depth (Turner and Delorme, 1996). The $^{210}$Pb analysis was carried out by MyCore Scientific Incorporated (Dunrobin, Ontario, Canada). For depths below which a reliable $^{210}$Pb age could be estimated, the mean sedimentation rate was used to extrapolate the chronology to the base of the cores.

Chironomid analysis followed standard procedures (Walker, 2001). To obtain a consistent temporal resolution, based on the $^{210}$Pb chronologies, chironomids were identified in sediment sampled from the cores at varying resolutions for the lakes that ranged from 0.5 cm to 1.0 cm. A minimum of 45 head capsules were enumerated and identified from each sample (Quinlan and Smol, 2001). Identifications were based on
Wiederholm (1983), Brooks et al. (2007), and an extensive reference collection housed at The Ohio State University. The volume of wet sediment needed to achieve the minimum number of head capsules varied between 0.25 mL and 3.0 mL.

2.4.3 Statistics, model development and application

The relative abundance of midge taxa at each site was plotted stratigraphically using the program C2 (Juggins, 2003). Zones were identified using optimal sum of squares partitioning as implemented by the program ZONE version 1.2 (Juggins, 1992). The statistical significance of the zonation was assessed with a broken stick model using the unpublished program BSTICK (Bennett, 1996). The timing, magnitude and rate of compositional change in taxa was assessed using detrended correspondence analysis (DCA) and implemented using the program CANOCO version 4.5 (ter Braak and Šmilauer, 2002).

The chironomid-based inference model for mean July air temperature (MJAT) was applied to the square-root transformed midge percent data for all the lakes. The chironomid-based inference model for MJAT was designed specifically for use in the Intermountain West (Porinchu et al., 2010). The chironomid-based inference model is based on 79 lakes and 54 midge taxa and makes use of a weighted averaging-partial least squares (WA-PLS) approach (ter Braak et al., 1993). The performance statistics for the two-component WA-PLS inference model, had an $r^2_{\text{jack}} = 0.55^\circ\text{C}$, RMSEP = 0.9$^\circ\text{C}$, and a maximum bias of 1.66 $^\circ\text{C}$. Further detail on the training set lakes and model performance are available in Porinchu et al. (2007b, 2010). The program C2 (Juggins, 2003) was used to develop the WA-PLS inference models and estimate sample-specific error (SSE).
2.5 Results

2.5.1 Core chronologies

Profiles of the $^{210}$Pb age to depth relationship, along with sedimentation rates are presented in Figure 2.2. The depth at which supported $^{210}$Pb reaches background levels varied amongst the lakes (Smith – 8 cm; Birdeye – 9 cm; Cold – 10 cm; Stella – 21 cm; Dead – 6.5 cm; Teresa – 5.5 cm), with the well-resolved section of each record spanning the following intervals: Smith Lake (AD 2010–1905), Birdeye Lake (AD 2010–1935), Cold Lake (AD 2011–1900), Stella Lake (AD 2011–1900), Dead Lake (AD 2010–1905), and Teresa Lake (AD 2010–1915) (Figure 2.2). The sedimentation rates, within the well-constrained sections identified above, display a coefficient of variation of between 2 and 17%. Overall the relatively uniform sedimentation rates and the existence of exponential $^{210}$Pb decay profiles (Figure 2.2) in six of the lake cores suggest that these chronologies should be considered reliable.

2.5.2 Loss-on-ignition

The LOI analysis indicates that all six lakes exhibited similar trends in the percent loss-on-ignition (Figure 2.3). The study lakes are characterized by relatively small catchment areas, with the exception of Teresa Lake (Table 2.1). Stella Lake was the most productive lake with LOI values ranging between 30% and 55%, far exceeding the LOI values of the other study sites. The drainage ratio (catchment area: lake surface area) indicates a large difference between Stella Lake (5.7) and the remainder of the lakes (25-
The LOI values for the basal sediment from Cold, Dead, Teresa, Birdeye, and Smith lakes vary between 10% and 20%, increasing to 20 to 40% in the upper sediment. The LOI profiles indicate that Cold and Smith lakes were the least productive of all the lakes with LOI values fluctuating around 10% through much of the 20th century.

2.5.3 Midge percentage diagrams

Fluctuations in midge community composition are presented in Figures 2.4a – 4f.

2.5.3.1 Smith Lake

A total of 15 midge taxa were identified in Smith Lake (SMT), clustered in three zones: SMT-I spans AD 1900 to AD 1959; SMT-II spans AD 1959 to AD 1990; and SMT-III spans from AD 1990 to the present. Procladius and Chironomus dominate SMT-I, with this zone also characterized by a slight decrease in Psectrocladius semicirculatus/sordidellus and Tanytarsus indeterminable. SMT-II is a transition zone with Tanytarsus indeterminable rising to a relative abundance of approximately 40% and Dicrotendipes appearing and increasing to a relative abundance of approximately 10% towards the top of this zone. Taxa that dominate the basal part of the core (Chironomus and P. semicirculatus/sordidellus) decrease to below 5% in SMT-II. In SMT-III, many taxa present in the basal sediment are nearly extirpated and replaced with thermophilous taxa such as Cladopelma and Dicrotendipes, with the latter continuing to increase through SMT-III and reaching a relative abundance of over 40% in AD 2000. Head capsule concentrations vary by zone in Smith Lake: SMT-I has the lowest values of ~100 mL⁻¹; SMT-II has the highest values reaching near 280 head capsules mL⁻¹; and
SMT-III features slightly lower values of ~ 160 head capsules mL⁻¹. Taxon richness for Smith Lake varies between 7.0 and 12.0 with a mean value of 9.5, with the SMT-II exhibiting the highest taxonomic richness.

2.5.3.2 Birdeye Lake

Birdeye Lake (BDY) contains a total of 12 midge taxa assembled into two zones: BDY-I (AD 1940-1970); and BDY-II (AD 1970-2010). The principal midge taxon in BDY-I is Cladotanytarsus mancus-group, comprising approximately 40% of the samples in this zone. The relative abundance of Procladius remains fairly consistent in Birdeye Lake fluctuating around 10% through both zones. The major shift in midge composition between BDY-I and BDY-II involves C. mancus-group and Tanytarsus type-G. The increased abundance of Tanytarsus indeterminable and Dicrotendipes in BDY-II relative to BDY-I is another distinguishing characteristic of BDY-II. Head capsule concentrations in Birdeye Lake remain fairly constant around 120 head capsules mL⁻¹, with the exception of two samples between three and four cm where head capsule concentrations increase to ~ 320 head capsules mL⁻¹. The taxon richness in Birdeye Lake varies from 5.0 to 12.0, with a mean value of 8.8.

2.5.3.3 Cold Lake

Cold Lake (CLD) features the most diversity of the lakes in this study with a total of 18 identifiable midge taxa. There are two zones demarcated by a notable shift in the midge community at AD 1970. The older zone, CLD-I, is characterized by a high relative abundance of Procladius and Sergentia, with the latter reaching upwards of 35% of the
total enumerated sub-fossils in this zone. CLD-I also contains low percentages of *Cricotopus/Orthocladius* and *Micropsectra*. A significant shift in community composition occurs at AD 1970 with *Procladius* and *Sergentia* greatly reduced in abundance. Taxa that continue to increase or appear for the first time in CLD-II include *C. mancus*-group, *Dicrotendipes, P. semicirculatus/sordidellus*, and *Corynoneura/Thienemanniella*. Head capsule concentration also varies throughout the core with basal sediments containing approximately 50 head capsules mL$^{-1}$ and a core maximum of 200 head capsules mL$^{-1}$ at approximately 5 cm. The upper sediment is characterized by very low head capsule concentrations, most likely due to the increased pore water and flocculent surface sediment. Taxon richness for Cold Lake varies between 8.0 and 14.0, with a mean value of 10.9.

2.5.3.4 *Stella Lake*

Stella Lake (SL) has a total of 12 identifiable midge taxa, although the diversity is fairly low with only seven taxa reaching above 5% abundance in the core. The first zone, SL-I, encompasses the basal portion of the core and is very similar in midge composition to SL-II, with a few exceptions. *Corynoneura/Thienemanniella* reaches its maximum, albeit a low relative abundance, and *Tanytarsus* indeterminable also has its maximum abundance in SL-I. SL-II spans most of the core, extending from ~ AD 1925 to the present. SL-II is dominated by several taxa including *Tanytarsus, P. semicirculatus/sordidellus*, and *Procladius*. Head capsule concentration is fairly uniform throughout the core, averaging around 130 head capsules mL$^{-1}$. The taxon richness from Stella Lake varies between 6.0 and 10.0, with a mean value of 8.1.
2.5.3.5 Teresa Lake

Teresa Lake (TL) is the least diverse of all the lakes in this study with 10 identifiable taxa, and only four of these taxa having a relative abundance of >5%. Taxon richness is also lowest amongst the lakes, varying between 4.0 and 8.0 with a mean value of 5.9. The core is dominated by the presence of *P. semicirculatus/sordidellus*, and *Chironomus*, with the former comprising greater than 50% of the remains enumerated in any given sample. Variations in the abundance of *P. semicirculatus/sordidellus* and *Cricotopus/Orthocladius* largely drive the zonation; a large increase in *Cricotopus/Orthocladius* in the upper sediment sample defines a statistically significant zone, TL-II. A large decrease in head capsule concentration and taxon richness is also notable in TL-II. The head capsule concentrations in Teresa Lake steadily decline from 175 head capsules mL\(^{-1}\) in the basal sediment to approximately 25 head capsules mL\(^{-1}\) in the surface sediment.

2.5.3.6 Dead Lake

Dead Lake (DL) consists of 11 identifiable midge taxa and was split into two significant zones. DL-I spans from approximately AD 1900 to AD 1940, and is dominated by a single taxon, *Chironomus*, comprising 50% of the midge community. DL-II spans from AD 1940 to the present and is dominated by three taxa; *Pentaneurini*, *Tanytarsus* indeterminable, and *Tanytarsus* type-G. Near the base of DL-II, *Tanytarsus* type-K rises to ~18% relative abundance then declines quickly and is extirpated from the core. *P. semicirculatus/sordidellus*, a temperate taxon, increases in abundance through DL-II. *Pentaneurini*, and *Tanytarsus* type-G, which are present at relatively low
abundances in DL-I, increase in DL-II. The head capsule concentrations average 100 head capsules mL$^{-1}$, with only one sample exceeding this, reaching a value of 300 head capsules mL$^{-1}$. The taxon richness from Dead Lake varies between 6.0 and 9.0 with a mean value of 7.4.

2.5.4 Ordination analyses

DCA of the subfossil midge assemblages reveals that a large amount of compositional turnover characterizes the late 20$^{\text{th}}$ and early 21$^{\text{st}}$ centuries in four of the six lakes: Smith, Dead, Cold, and Birdeye (Figure 2.5). A striking feature is the unidirectional compositional change that occurs post AD 1970. However, Stella and Teresa lakes display very little species turnover throughout the 20$^{\text{th}}$ and 21$^{\text{st}}$ centuries. This is most likely the result of the low alpha diversity and the dominance of few taxa in the Stella Lake and Teresa Lake midge communities.

2.5.5 Chironomid-based temperature reconstructions

The taxa present are well-represented and characterized by the Intermountain West calibration set (Porinchu et al., 2010). Since all 18 of the chironomid taxa comprising the chironomid stratigraphy reported in this study are present in the training set, the MJAT reconstructions are considered reliable. Values ranging between 2 and 23 for Hill's N2 diversity index (Hill, 1973) provide added support that the quantitative chironomid-based MJAT reconstructions can be considered reliable (Birks, 1998).

The chironomid-based temperature inference for MJAT are illustrated in Figure 2.6. The inferences for Cold Lake, Birdeye Lake, and Smith Lake show similar trends in...
the MJAT during the 20th century. Stella Lake also shows very similar trends to Cold, Birdeye and Smith lakes, however the MJAT for Stella Lake is characterized by a large sample-to-sample variability. Teresa Lake and Dead Lake, exhibit a highly variable MJAT throughout the 20th century. The average MJAT for Smith Lake = 10.4°C; Birdeye Lake =10.1°C; Cold Lake = 11.0°C; Stella Lake = 11.2 °C; Teresa Lake = 11.6°C and; Dead Lake = 10.8°C. The range in chironomid-inferred MJAT for the lakes is: Smith Lake = 0.8°C; Birdeye Lake = 1.0°C; Cold Lake = 1.6°C; Stella Lake = 0.7 °C; Teresa Lake = 1.0°C and; Dead Lake = 1.0°C. The sample-specific error estimates associated with the MJAT inferences varied between 1.0°C and 1.9°C. All of the lakes experience their highest chironomid-inferred MJAT in the post-AD 1980 interval, with the exception of Teresa and Dead lakes. A LOWESS smoother (span = 0.4) was applied to the reconstructions from all the lakes to highlight the main trends in MJAT over the entire record (Figure 2.6). The large increase in MJAT in the post-AD 1980 interval in four of the lakes: Smith, Cold, Birdeye and Stella is the most notable feature of the reconstructions, with the expectation of the slight cooling in the upper most samples of Stella Lake. The rate of temperature change between AD 1920 and AD 2010 for Smith Lake = 0.6°C/100 years; Birdeye Lake =0.7°C/100 years; Cold Lake = 1.2°C/100 years; Stella Lake = 0.4°C/100 years. The rate of warming increased slightly in the post-AD 1970 interval, with Smith Lake = 1.5°C/100; Birdeye Lake =1.6°C/100 years; Cold Lake = 1.4°C/100 years; Stella Lake = 0.8°C/100 years.

A plot of deviations of MJAT from the long-term average for all the lakes for the period AD 1895-2012 is depicted in Figure 2.7. The deviation of July air temperature
from Nevada Climate Division #2 (NV#2), which encompasses the region, is also illustrated in Figure 2.7. For the early 20th century the northeast portion of Nevada was characterized by average or below average chironomid-inferred temperature. Nevada Climate Division #2 with the exception of the 1930’s also experiences an average or below average air temperature during the early 20th century. Starting around AD 1950 and extending to AD 1990 the lake and the climate division data exhibit similar temperature trends. Post-AD 1990, Cold Lake, Birdeye Lake, Smith Lake, and Nevada Climate Division #2 all experience above average chironomid-inferred MJAT and air temperatures. The long-term trends of chironomid-inferred MJAT and Nevada Climate Division #2 air temperatures display a strong correspondence throughout most of the 20th and 21st centuries.

2.6 Discussion

Chironomid-based inference models were first used to examine the large swings in temperature, on the order of 10°C, that characterized the circum-North Atlantic region during the Pleistocene-Holocene transition (Walker et al., 1991; Cwynar and Levesque, 1995; Brooks and Birks, 2001). Reconstruction of late-glacial climate conditions using sub-fossil midge analysis worked extremely well, in part, because the magnitude of temperature change was much larger than the RMSEP and maximum bias of the inference models and the estimated sample-specific errors of the reconstructions. Follow-up studies have extended high-resolution sub-fossil midge analysis to the recent past by successfully demonstrating that midges are sensitive to the smaller magnitude changes in temperature that characterize much of the Holocene (Larocque and Hall, 2003; Solovieva
et al., 2005; Porinchu et al., 2007a). These studies have demonstrated, through comparison to observational data gathered during the 20th century, that the midges are capable of resolving changes in air and surface water temperature on the order of 1-2°C. Chironomid-based paleotemperature reconstructions that also incorporate inferences of climate and environmental change available from other proxy sources result in an improved understanding of overall environmental change during the Holocene (Battarbee et al., 2002; Smol et al., 2005; Birks and Birks, 2006; Larocque-Tobler et al., 2012).

In this study, the results of a multi-proxy examination of six lakes located along a 300 km north-south transect in the central Great Basin are presented (Figures 2.6 & 2.7). The environmental change evidenced by the LOI data and the sub-fossil midge assemblages is consistent amongst the majority of sites but notable site-specific differences do exist. Examination of the biotic and geochemical properties (Reinemann et al. under review) of the lake sediment records, together with knowledge of the local catchment conditions and characteristics, provides insight into the relative importance of temperature in influencing midge community composition during the 20th century. Productivity, as estimated by LOI, remains relatively constant in all lakes prior to about AD 1970, after which it begins to rise (Figure 2.3). It is important to note that LOI can be influenced by: (1) sediment composition through changes in lake productivity (autochthonous inputs) and catchment conditions (allochthonous inputs); and (2) sediment accumulation through changes in basin morphology and lake level. Therefore, LOI values reported from a single core must be interpreted with caution (Shuman, 2003). The increase in LOI in the upper sediment likely reflects the differing degrees of
decomposition and sediment composition in the surface. A similar trend of increasing LOI is observed in the recently deposited sediment from lakes in arctic, alpine and sub-alpine settings (Landers et al., 2008; Porinchu et al., 2009; Mast et al., 2010; Hobbs et al., 2011; Medeiros et al., 2012).

A relatively strong correspondence exists between the chironomid-inferred MJAT reconstructions for Cold, Smith, Birdeye, and Stella lakes and observed MJAT for Nevada Climate Division #2 for the late 20th century (Figure 2.7). All four lakes experience above average temperatures in the post-AD 1980 interval, with the instrumental data displaying similar elevated temperatures during the last three decades. The persistent above average chironomid-inferred temperatures that characterize the last three decades are evident in other regional records from the Great Basin (Porinchu et al. 2007b; 2010). Midge communities in the Sierra Nevada (Porinchu et al., 2007a); Snake Range (Porinchu et al., 2010), and the Uinta Mountains (Porinchu, unpublished data) have been documented as responding to elevated air and water temperature during the late 20th century. The rates of warming reported in this study are similar to those from around the region (Porinchu et al., 2007b, 2010). The response of midge communities to radiatively forced temperature rise is consistent with studies that have identified the importance of local climatology in influencing the physical, chemical and biological character of lakes (Parker et al., 2008; Hobbs et al., 2011; Garcia-Jurado et al., 2012; Saros et al., 2012). The elevated temperatures characterizing the post-AD 1980 interval identified in four of the lakes in this study also correspond to studies documenting recent
changes in hydroclimate in the western United States (Cayan et al., 2001; McCabe and Clark, 2005; Rauscher et al., 2008; Saunders et al., 2008; Brown and Kipfmuller, 2012).

The chironomid-based temperature reconstructions from Teresa and Dead lakes do not correspond to the reconstructions for the other four lakes in this study or the climate data from Nevada Climate Division #2. The discrepancy between the Teresa Lake and Dead Lake reconstructions and the instrumental record may be related to site-specific catchment or limnological conditions. Examination of DCA axis-1, which in the other four lakes corresponds well to chironomid-inferred MJAT, underscores the potential influence of site-specific or catchment conditions on midge community composition and turnover. Dead Lake is the smallest and shallowest lake in this study. Given the relatively small volume of the lake (see Table 2.1), Dead Lake would be highly susceptible to lake drawdown and possibly desiccation during sustained intervals of decreased effective moisture. Lake drawdown would significantly alter limnological conditions and thereby affect midge community composition in a manner independent of temperature. Teresa Lake is fed largely by groundwater, some of which emanates as melt from the Wheeler Peak rock glacier. Repeat measurement indicates that the temperature of inflowing groundwater remains constant at ~1.5°C throughout the summer, before drying/freezing in the late fall-early winter (Mark, unpublished data). Although lake water temperatures do co-vary with air temperature (Larocque et al., 2001), the influence of elevated air temperature on the midge community at Teresa Lake may be mediated by the groundwater flux. The input of cold groundwater may lead to the midge community being de-coupled from fluctuations in air temperature.
If Teresa Lake and Dead Lake are removed from the comparison, a coherent regional picture emerges. Sub-alpine and alpine lakes in the central Great Basin have experienced above average temperatures, relative to the entire 20th century, in the post-AD 1980 interval (Figure 2.7). Interestingly, a spatial pattern appears to be evident in the magnitude and timing of the response of the midge communities to the elevated temperatures that characterize this region during the late 20th century and early 21st century. The northern sites appear to respond more strongly to the warming (Figure 2.6 & 2.7), while the southern sites, Stella Lake (this study) and Baker Lake (Porinchu et al., 2010) do not appear to be responding as quickly or as strongly to the change in observed air temperatures. This is evident in the rates of warming over the last 100 years, on average 0.9°C for the northern sites and 0.5°C for the southern sites (Porinchu et al., 2010) and during the post-AD 1970 interval. This observed spatial variability in midge community response to the elevated temperatures that characterize the central Great Basin during recent decades could be due to: (1) complex interactions that exist between hydroclimate, catchment processes and limnology; or (2) the lower elevation of the northern sites compared to the southern sites, especially in the Great Basin where topography can greatly influence the local environmental conditions (Wise, 2012).

It is important to note that midge communities can be influenced by factors other than temperature. Other studies have identified food and habitat availability, nutrient loading and lake level fluctuations as factors influencing midge community composition. Some of the earliest studies involving chironomid communities involve lake trophic status classification schemes based on the distribution of taxa, as reviewed by Lindegaard.
(1995). More recently, Brodersen and Quinlan (2006) demonstrated the influence of lake trophic status and hypolimnetic oxygen conditions on chironomid communities. Adaptations have allowed some chironomid species to survive in low oxygen concentrations and these adaptations can influence chironomid distribution (Brodersen and Quinlan, 2006). Many studies have also demonstrated the importance of lake level on the distribution of chironomid communities, through its effect on water temperature, oxygen availability, and food quantity (Kurek and Cwynar, 2009; Engels and Cwynar, 2011; Cwynar et al., 2012). Another factor that could be influencing faunal composition is the documented increase in lake productivity, as estimated by LOI, during recent decades (Figure 2.4) (Velle et al., 2010). Nitrogen deposition to high-elevation lakes in the Rocky Mountains and elsewhere in the region, which has increased in recent decades, may also be influencing midge community composition (Sickman et al., 2003; Wolfe et al., 2003; Moser et al., 2010; Saros et al., 2011). As mentioned above, LOI, although a crude approximation for lake productivity, has exhibited an increase in all lakes post-AD 1970. However, the lake productivity does not appear to be influencing the midge communities in this study. For example, Smith Lake and Birdeye Lake exhibit the largest increase in chironomid-inferred MJAT post-AD 1970, coincident with the smallest increase in LOI (Figures 2.4 & 2.6). Further confidence in the chironomid-inferred MJAT is gained from the correspondence between the instrumental records and DCA axis one, representing faunal turnover, and the inferred temperatures.

The varied characteristics of the lakes incorporated in this study have also provided the opportunity to identify criteria that can be used to improve site-selection for
longer-term temperature reconstructions in the Intermountain West. Site-selection criteria have been identified elsewhere (Smol et al., 2001); however, some of the criteria we identify as significant are specific to the Great Basin region. In arid and semi-arid environments, such as those that characterize much of the Great Basin, lakes are typically only found in the upper reaches of a drainage basin near the headwalls of catchments.

From the results of this study it is clear that a lake requires a sufficiently large volume of water to limit the influence of fluctuating lake levels on midge community composition, e.g., Dead Lake. In addition, the contribution of cold, glacial meltwater or spring water must be minimized, especially if attempting to solely develop air temperature reconstructions. For example, the midge community in Teresa Lake is characterized by low taxonomic diversity and is most likely a response to the principal control of a meltwater spring that keeps the lake at a uniform temperature through the summer months and allows for cold water pooling in the benthic zone of the lake. A more detailed study of the thermal characteristics of a potential study-site would be beneficial before selecting it for use in a long-term temperature reconstruction (Smol and Last, 2001). However, this study also suggests that application of surface water temperature and air temperature inference models, to midge stratigraphies from carefully selected sites, may provide a means to quantify the varying influence of glacial meltwater flux to alpine and sub-alpine lakes through the Holocene.

This study further supports earlier research from western United States and other regions, mainly Europe, documenting recent changes in midge communities in sub-alpine and alpine lakes (Battarbee et al., 2002; Solovieva et al., 2005; Porinchu et al., 2007a,
Changing thermal conditions, due to radiative forcing, has been implicated in numerous studies as a driver of the observed shift in midge community composition (Solovieva et al., 2005; Porinchu et al., 2010; Larocque-Tobler et al., 2011). With a better understanding of the controls on chironomids during the instrumental interval (150 years), where comparison to independent records are possible, a better understanding of the chironomid-temperature relationship can be gained (Eggermont and Heiri, 2012) and greater confidence can be placed in chironomid-based Holocene temperature reconstructions (Porinchu et al., 2007a). Specifically, the results from this study further reinforce the link between climate change and midge communities, thus supporting the continued use of midges in developing longer-term paleotemperature reconstructions. This work also establishes a regional limnological baseline that will both help to identify the degree to which aquatic ecosystems in these vulnerable regions have been or are being impacted by anthropogenic activities (Wolfe et al., 2003; Karst-Riddoch et al., 2005), and provide a long-term context to evaluate future changes in aquatic ecosystem structure and function (Swetnam et al., 1999; Smol, 2008).

2.7 Acknowledgements

We thank Gretchen Baker (Staff Ecologist, Great Basin National Park, GBNP), Andrew J. Ferguson (Superintendent, GBNP) and United State Forest Service (USFS) for providing access to the research sites and facilitating our research. We also thank Paul Soltesz, Jim DeGrand, Christina Zerda, Brian Shell, and Nate Patrick for their unyielding assistance in the field. We acknowledge The Western National Park Association.
(WPNA), the Department of Geography at The Ohio State University, and a NSF Doctoral Dissertation Improvement Grant to D. F. Porinchu and S.A. Reinemann (BCS-1130340) for funding this research.
2.8 References


Juggins, S., 2003: Program C2 Data Analysis.


Larocque-Tabler, I., Quinlan, R., Stewart, M. M., and Grosjean, M., 2011: Chironomid-inferred temperature changes of the last century in anoxic Seebergsee, Switzerland:


### Table 2.1

<table>
<thead>
<tr>
<th>Variables</th>
<th>Smith Lake</th>
<th>Birdeye Lake</th>
<th>Cold Lake</th>
<th>Stella Lake</th>
<th>Teresa Lake</th>
<th>Dead Lake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year Cored</td>
<td>2010</td>
<td>2010</td>
<td>2011</td>
<td>2011</td>
<td>2010</td>
<td>2010</td>
</tr>
<tr>
<td>Elevation (m a.s.l.)</td>
<td>2780</td>
<td>2854</td>
<td>3015</td>
<td>3175</td>
<td>3135</td>
<td>2916</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>3.60</td>
<td>3.85</td>
<td>6.00</td>
<td>1.50</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Lake Volume (m$^3$)</td>
<td>31,460</td>
<td>11,760</td>
<td>12,380</td>
<td>9,350</td>
<td>8,450</td>
<td>780</td>
</tr>
<tr>
<td>Surface Area (ha)</td>
<td>1.8</td>
<td>0.6</td>
<td>0.4</td>
<td>1.9</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>Catchment Area (ha)</td>
<td>63.9</td>
<td>15.2</td>
<td>40.5</td>
<td>17.0</td>
<td>107.9</td>
<td>5.2</td>
</tr>
<tr>
<td>Drainage Ratio (catchment:lake surface)</td>
<td>33.6</td>
<td>25.3</td>
<td>101.3</td>
<td>8.9</td>
<td>154.1</td>
<td>52.0</td>
</tr>
<tr>
<td>Secchi Depth (m)</td>
<td>Unlimited</td>
<td>Unlimited</td>
<td>5.12</td>
<td>Unlimited</td>
<td>Unlimited</td>
<td>Unlimited</td>
</tr>
<tr>
<td>Measured SWT ($^\circ$C)</td>
<td>15.09</td>
<td>17.05</td>
<td>10.07</td>
<td>13.77</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

*Sensor malfunction.*
Figure 2.1 Location of study site lakes in the Great Basin of western United States (inset). The six lakes are located within the East Humboldt, Ruby Mountains and Great Basin National Park (boundary plotted on map). Nevada counties and major lakes are labeled for reference.
Figure 2.2 Radiometric chronologies for Smith, Birdeye, Teresa, Dead, Cold and Stella lakes depicting the constant rate of supply model and sedimentation rates. Note the different vertical axes for depth and sedimentation rates.
Figure 2.3 Loss-on-Ignition (%) conducted at 550°C from Cold (black circle), Stella (grey downward triangle), Dead (grey square), Teresa (grey diamond), Birdeye (grey upward triangle), and Smith (light grey circle) lakes graphed with respect to time.
Figure 2.4a – c. Chironomid stratigraphies for Smith (a), Birdeye (b), Cold (c), Stella (d), Teresa (e), and Dead (f) lakes. The order is based on the lakes’ location from north to south (matching Fig. 7). Taxa have been arranged according to their MJAT optima from the chironomid-based inference model, with decreasing optima temperature from left to right. Horizontal lines divide chrono zones, as identified in the text. Abbreviations for chironomid taxa: *Psectrocladius semi/sordi-type = Psectrocladius semicirculatus/sordidellus.* (continued)
Figure 2.4d – f (continued)
Figure 2.5 Detrended Correspondence Analysis (DCA) Axis 1 plotted against age for Smith, Birdeye, Teresa, Dead, Cold and Stella lakes. Heavy dashed lines represent a LOWESS smoother (span = 0.40).
Figure 2.6 Chironomid-based mean July air temperature reconstructions for Smith, Birdeye, Teresa, Dead, Cold and Stella lakes. Points represent chironomid-based MJAT inferences, with positive SSE plotted in light gray. The dotted line is the average chironomid inferred temperature for the entire interval of each lake. The heavy dashed line represents a LOWESS smoother (span = 0.40).
Figure 2.7 Deviations of the chironomid-based MJAT from the long term mean of each lake ordered based on the lakes’ location (Fig. 1) from north (Smith Lake) to south (Dead Lake). Deviations of air temperature over the period AD 1895-2012 for Nevada Climate Division #2, which encompasses all the lake sites. Thick line represents a LOWESS smoother (span = 0.4).
3 Chapter 3: A 2000 year reconstruction of air temperature in the Great Basin of the United States with specific reference to the medieval climatic anomaly

3.1 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 ($r^2_{\text{jack}} = 0.55$, RMSEP = 0.9°C). The chironomid-based MJAT reconstruction suggests that the interval between AD 900 and 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.
3.2 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 ‘mega droughts’ 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 Rouston 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 which plays 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 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, multi-decadal, 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 (multi-decadal resolution), paleotemperature record for the Great Basin spanning the last 2000 years. 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 paleoclimatic reconstructions from the Great Basin and hemispheric temperature compilations. Our intention is to examine how radiative forcing during the last two millennia, with specific reference to the MCA, influenced thermal conditions in the central Great Basin.

3.3 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 southern Great Basin occurs during the summer and is typically associated with the North American Monsoon (NAM) (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 changes in the tropical Pacific (Wise, 2012).

3.3.1 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 (Figure 3.1). 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 a.s.l. (Reinemann et al., 2011). Stella Lake is underlain by quartzite of Precambrian and Cambrian age, 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).

3.4 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, 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 3.1). The radiocarbon dates were provided by three laboratories (Table 3.1). 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 \textit{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 cm³ 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). 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) 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 of the variance in the fossil data than most of the 999 reconstructions trained on random environmental data drawn from a uniform distribution.

3.5 Results

3.5.1 Chronology and loss-on-ignition

The chronology, established by six AMS radiocarbon dates, indicates that the upper section of the core spans approximately 2000 years (Table 3.1 & Figure 3.2). 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 0.113 cm year\(^{-1}\) over the last two millennia. The age-depth model and sampling interval result in a multi-decadal sample resolution (~25 years 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 years. 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%.

3.5.2 Chironomid Community Change

A total of twelve midge taxa were identified in the Stella Lake core (Figure 3.3). 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 cm³. Significant changes in sub-fossil chironomid community composition resulted in identification of four zones (SL-I to SL-IV), representing distinct transitions. The midge community present in Zone SL-I (BC 100–AD 550 AD) is dominated by *Cladotanytarsus mancus* group and *Tanytarsus* with lesser amounts of *Procladius*, and *Tanytarsus* type H. This zone is also characterized by 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 *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.

3.5.3 Chironomid-based MJAT reconstruction

The taxa present in Stella Lake are well-represented and characterized by the Intermountain West 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 should 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* (Figure 3.4). The chironomid-inferred MJAT reconstruction for Stella Lake is presented in Figure 3.5. 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 (Figure 3.5). Between AD 0 and AD 600 the MJAT remained low, approximately 1.0°C below the 2000 year 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 remain there, their highest levels for the past 2000 years. 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 years was 3.0°C (9.4–12.4°C).

3.6 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 (Figure 3.5). 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 as 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 (Figure 3.6) 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 at AD 700, corresponds to the warming documented in Northern Hemisphere reconstructions (Figure 3.6) (Moberg et al., 2005; Mann et al., 2009; Christiansen and Ljungqvist, 2012) and pollen-based reconstructions for North America (Moinuddin et al., 2013). The MCA interval between AD 900 and AD 1300 exhibited a local maximum in chironomid-inferred temperatures at Stella Lake of approximately 0.4°C above the late Holocene average, with a sustained peak chironomid-inferred MJAT occurring between AD 800 and AD 950. The elevated temperatures which characterize Stella Lake during the late 1st millennium correspond to the warming evidenced 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 year 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 (Figure 3.6). The lowest temperature during the second millennium occurs at approximately AD 1500 matching the timing of greatest hemispheric temperature anomaly during the last 2000 years 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 onset of the recent warming plateau occurs earlier than many other records (Figure 3.6). 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 (Figure 3.2). It is notable that the recent warming, which exceeds MCA conditions, is in agreement with large-scale reconstructions for the past 1000 to 2000 years (Figure 3.6; 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 (Figure 3.7). In addition, Salzer et al. (2009) observed a slight increase in ring widths between AD 900 and AD 1200 and interpreted this as reflective of warmer growing season temperatures (Figure 3.7). 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 as an interval of increased aridity. The enhanced aridity has been linked to trends in the Pacific (Seager et al., 2007a) and variations in the strength of the NAM (Asmerom et al., 2007). Barron and Bukry (2007) suggest that the Gulf of California
experienced an interval of lower SSTs in middle of the MCA, indicating a weakening of the monsoon and associated monsoonal precipitation (Mitchell et al., 2002). Additional proxy records, although of relatively coarser resolution, suggest the NAM weakened in intensity during the late Holocene (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., 2007a) 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 dominated any influence temperature would have intensifying aridity (Seager et al., 2007a).

Current instrumental data show 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, 2012; Shinker and Bartlein, 2010). 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). Increasing the number of high-resolution, quantitative reconstructions of multi-decadal climate variability will improve our understanding of how recent climate perturbations such as the MCA and the LIA were manifested in the Great Basin (Diaz et al., 2011).

3.7 Conclusion

This quantitative multi-decadal chironomid-based temperature reconstruction from Stella Lake provides much need insight into thermal variability in the central Great Basin for the last two millennia. 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 supports 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., 2007b). 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 can be expected (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.

3.8 Acknowledgements

We would like to thank Gretchen Baker (Staff Ecologist, GBNP) and Andrew J. Ferguson (Superintendent, GBNP) for providing access to the research sites and facilitating our research, and Terry and Debbie Steadman for providing logistical support and local knowledge. We also thank Adam Herrington for his unyielding assistance in the field. We acknowledge The Western National Park Association (WPNA) and the Department of Geography at The Ohio State University for funding this research. We are grateful to suggestions offered by two anonymous reviewers and to the careful editing
and numerous suggestions of the journal editor.
3.9 References


Mann, M.E., Zhang, Z.H., Hughes, M.K., Bradley, R.S., Miller, S.K., Rutherford, S., Ni, F.B., 2008. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. Proceedings of the National Academy of


Table 3.1 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.

<table>
<thead>
<tr>
<th>Lab Code</th>
<th>Depth in core (cm)</th>
<th>Material</th>
<th>$^{14}$C yr BP</th>
<th>$\pm$</th>
<th>2σ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS-65913</td>
<td>33.00</td>
<td>Conifer Needle</td>
<td>185</td>
<td>30</td>
<td>1651 to 1954</td>
</tr>
<tr>
<td>11919</td>
<td>51.00</td>
<td>Conifer Needle</td>
<td>360</td>
<td>20</td>
<td>1456 to 1631</td>
</tr>
<tr>
<td>11920</td>
<td>60.5</td>
<td>Bark Fragment</td>
<td>420</td>
<td>20</td>
<td>1436 to 1487</td>
</tr>
<tr>
<td>262566</td>
<td>70.25</td>
<td>Conifer Needle</td>
<td>1250</td>
<td>40</td>
<td>675 to 873</td>
</tr>
<tr>
<td>262567</td>
<td>77.50</td>
<td>Conifer Needle</td>
<td>1640</td>
<td>75</td>
<td>240 to 571</td>
</tr>
<tr>
<td>OS-64648</td>
<td>115.00</td>
<td>Twig</td>
<td>2080</td>
<td>35</td>
<td>-195 to -2</td>
</tr>
</tbody>
</table>
3.11 Figures

Figure 3.1 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).
Figure 3.2 Age-depth model for the sediment core from Stella Lake (grey), overlaying the calibrated distributions of individual dates (blue). Grey dots indicate the model’s 95% probability intervals as outputted by *bacon* routine (Blaauw and Christen, 2011). The upper left inset show 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).
Figure 3.3 Chironomid relative abundance diagram for Stella Lake. Taxa have been arranged according to their MJAT optima from the midge-based inference model, with decreasing optima temperature from left to right. *Psectrocladius semi/sordid-type = Psectrocladius semicirculatus/sordidellus.*
Figure 3.4 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 3.5 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 grey line represents DCA axes 1 scores.
Figure 3.6 Summary diagram of select hemispheric and regional temperature reconstructions based on model and paleo-proxy data and data from Stella Lake. (a) Northern Hemisphere mean temperature variations (grey) and its >80-yr component (black) (Moberg et al., 2005), (b) Reconstruction of extra-tropical Northern Hemisphere mean temperature variations (grey) and 50-yr smooth (black) (Christiansen and Ljungqvist, 2012), (c) mean temperature deviations from 1000-1990 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 (grey) and loess smooth (span = 0.2) (black) and (d) Stella Lake chironomid-inferred MJAT (black) and loess smooth (span = 0.2) (grey). Gray shading represents the MCA interval (AD 900 – 1300).
Figure 3.7 Summary diagram of select 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 year median) (Salzer et al., 2009), and (d) Stella Lake chironomid-inferred MJAT (black line) and loess smooth (span = 0.2) (grey line). Gray shading represents the MCA interval (AD 900 – 1300).
Chapter 4: A regional synthesis of climate change during the Holocene from the central Great Basin.

Scott A. Reinemann¹*, David F. Porinchu², Bryan G. Mark¹, and Jeffery S. Munroe³

¹ Geography Department, The Ohio State University, Columbus, OH 43210
² Geography Department, University of Georgia, Athens, GA 30602
³ Geology Department, Middlebury College, Middlebury, VT 05753

4.1 Abstract

Lake sediment cores spanning roughly the last 7,000 years were recovered from four small sub-alpine and alpine lakes located in central Great Basin of the United States. The cores were analyzed for subfossil chironomid (non-biting midges) and organic content (estimated by loss-on-ignition (LOI)). LOI analyses indicate that the minor fluctuations in organic content that characterized all the sites through much of the mid-Holocene, was followed by a rapid increase in lake organic matter content during the last 200 years, with the exception of Angel Lake. Detrended correspondence analysis (DCA) documents notable faunal turnover at all sites during the late Holocene. Reconstructions of mean July air temperature (MJAT) were developed for each of the study sites using a chironomid-based inference model for MJAT (two-component WA-PLS) consisting of 79 lakes and 54 midge taxa ($r^2_{\text{jack}}=0.55$, RMSEP=0.9°C). The Stella Lake reconstruction,
which provides the most robust MJAT inferences, indicates that the MJAT characterizing the southern portion of the study transect, at approximately 5500 cal yr BP is approximately 0.2°C higher than the long-term average. The elevated temperature that characterizes the mid-Holocene at Stella Lake is surpassed only during the Medieval Climate Anomaly and the post-AD 1800 interval. The reconstructions for the sites located in the northern portion of the study transect are characterized by greater variability, likely reflecting the influence of both radiative forcing and catchment-specific conditions.

4.2 Introduction

In recent decades, great progress has been made in developing quantitative, high-resolution records of global and hemispheric patterns of past climate variability (Mann et al., 2008; Kaufman, 2009; Ljungqvist, 2010). Global climate models and attribution studies have greatly improved our understanding of anthropogenic and natural drivers of climate change and their relative contribution to observed warming (Tett et al., 2002; IPCC, 2007; Trouet et al., 2009). These studies, which provide valuable and much needed data on global and hemispheric climate trends in temperature (e.g. mean annual temperature (MAT), diurnal temperature range (DTR)), and precipitation are often cited when placing recent climate change in context, as well as when discussing and assessing our ability to adapt to future climate variability and change. However, the trends highlighted in these studies often mask the heterogeneous response of the climate system at finer spatial scales, and as a result these global and hemispheric-scale studies are not sufficient for documenting possible future conditions at the regional and sub-regional
scale. Improving our understanding of regional climate dynamics, as well as recognizing the importance of spatial variability in controlling regional patterns, will significantly improve our ability to model regional response to future climate forcings. This is especially important because much of the uncertainty in model simulations of future conditions centers on the impacts associated with regional climate change (Mitchell and Hulme, 1999; IPCC, 2007). An outstanding opportunity exists to focus on developing well-constrained, quantitative proxy-based records of the regional changes associated with past warm climate events, such as the Medieval Climate Anomaly (MCA) and the Holocene Thermal Maximum (HTM). Improving our understanding of regional patterns of past climate change and variability will enable climate scientists to evaluate the forcings and mechanisms underlying these perturbations and better constrain regional climate simulations and projections of future conditions.

The HTM can provide an analogue for understanding climate impacts in the Great Basin during a transition to warmer and more arid conditions. The HTM is believed to have resulted from an increase in seasonality and solar insolation during the early to mid-Holocene (Thompson et al., 1993; Wigand and Rhode, 2002; Harrison et al., 2003). Projected warming in the Great Basin is linked to increased atmospheric greenhouse gas concentrations resulting in an enhanced greenhouse effect, which in turn would lead to radiative forcing of the climate system. Another mechanism projected to influence future climate in the Great Basin involves the northward migration of the poleward limb of the Hadley cell in response greenhouse gas forcing (Lu et al., 2007) and stratospheric ozone depletion (Kang et al., 2011). The poleward expansion of Hadley cell would produce
more sinking air over the sub-tropics, leading to clearer skies and warm, arid conditions in the Great Basin (Harrison et al., 2003). A similar configuration existed during the HTM when the remnants of the Laurentide Ice Sheet were restricted to northeastern Canada and the position of the polar jet stream had shifted poleward (Bartlein et al., 1998; Dyke et al., 2002). Although the forcings responsible for the HTM and the elevated temperatures projected to occur during the 21st century are not identical it nevertheless would be beneficial to examine the response of regional climate to these perturbations in the early to mid-Holocene. Most HTM climate syntheses are based on modeling studies (Bartlein et al., 1998; Brown et al., 2008; Renssen et al., 2012) or paleoclimate data derived from global datasets (Thompson et al., 1993; Mock and Brunelle-Daines, 1999; Thompson and Anderson, 2000; Wanner et al., 2008), and have provided coarsely resolved results expressed in terms of “warmer than present,” “cooler than present,” or “no change.” A detailed examination of the magnitude and timing of the HTM at the regional scale could help to constrain the Global Circulation Models (GCM) and Regional Circulation Models (RCM) and provide valuable field-based observational data that can be used to test the influence of various forcing mechanisms associated the HTM.

Holocene climate in western North America is believed to be controlled by the long term changes in insolation and the northward migration of the polar jet stream following the Last Glacial Maximum (LGM) (Bartlein et al., 1998). Regional paleoecological and paleoclimate records suggest that the HTM, which is associated with enhanced aridity in North America, occurred between 7,000 and 4,000 cal yr BP in the Great Basin (Mock and Brunelle-Daines, 1999; Wigand and Rhode, 2002; Tausch et al.,
However, most of these paleoclimate records are qualitative in nature, with very few of the records providing continuous, quantitative estimates of temperature or precipitation change during the mid-Holocene. If we are to assess what future climate may approximate, it is important to examine a longer time frame than instrumental climate records allow. Quantitative paleoclimate records will help in examining long-term trends and shifts in local and regional climate (Mock and Brunelle-Daines, 1999).

This study investigates the changing thermal and environmental conditions at four sub-alpine and alpine lakes in the central Great Basin during the mid- to late-Holocene, making specific reference to the HTM. The lake sediment cores have been chronologically constrained using accelerated mass spectrometry (AMS) $^{14}$C. Detrended correspondence analysis (DCA) was implemented to evaluate the timing and magnitude of compositional turnover in the lakes. Lastly, we applied a chironomid-based MJAT inference model (Porinchu et al., 2010) to develop MJAT reconstructions spanning the mid- to late-Holocene for central Nevada. The results from Stella Lake, the most robust reconstruction, are compared to regional and hemispheric paleoclimate records to examine the correspondence between regional and hemispheric conditions during the mid- to late Holocene and examine how temperature and moisture interact to enhance regional aridity (Benson et al., 2002; Mensing et al., 2004; Woodhouse, 2004). The results obtained from the multi-site application of the MJAT inference model highlight the challenges that exist when attempting to reconstruct muted Holocene temperature change using sub-fossil midge (Velle et al., 2010; Brooks et al., 2012; Eggermont and Heiri, 2012).
4.3 Study Area

The study sites are located in the Great Basin of the western United States (Figure 4.1). The Great Basin is characterized by horst and graben topography. The presence of alternating high mountain ranges and long narrow valleys allow for large local variations in temperature and precipitation. The mountain ridges experience mean winter (December, January, February) temperatures of approximately -7 °C and mean summer (June, July, August) temperatures of 13.5 °C, while the valley floors experience mean summer temperatures of 22 °C and mean winter temperatures of -1.0 °C (WRCC, 2012). Overall, precipitation is limited in the Great Basin due to its location on the lee side of the Sierra Nevada, and it ranges from approximately 100 mm to 450 mm annually, resulting in a semi-arid to arid climate. Precipitation maxima vary from winter to spring over the entire Great Basin, with some areas experiencing a summer maximum due to convective storm activity (Wise, 2012; WRCC, 2012).

Angel Lake (41.026589°N, 115.087003°W) is located in the East Humboldt range of central Nevada at an elevation of 2560 m asl. The lake covers an area of 4.7 ha and has a maximum depth of 11 m. Soldier Lake (40.733951°N, 115.274022°W) is located in the northern Ruby Mountains of central Nevada at an elevation of 2782 m asl and is situated on a long north-south trending elevated plateau on the northeastern side of the Ruby Mountains. The lake is small only covering an area of 2.0 ha with a maximum depth of 3.6 m. Overland Lake (40.459554°N, 115.456696°W), located in the southern Ruby Mountains at an elevation of 2880 m asl, covers an area of 4.8 ha and has a maximum depth of 18 m. Stella Lake (39.005332°N, 114.318686°W), located in the Snake Range of
eastern Nevada at an elevation of 3170 m asl, covers an area of 1.9 ha and has a maximum depth of 1.5 m.

4.4 Methods

4.4.1 Sediment Recovery

The Stella Lake and Soldier Lake sediments were recovered using a modified Livingstone piston corer, while the Overland Lake and Angel Lake sediments were recovered with the use of a percussion corer. All cores were taken from a floating platform in the deepest portion of the lake. The cores were extruded in the field into one meter long black PVC tubes and transported to The Ohio State University (Stella, Soldier) or Middlebury College (Angel, Overland). The surface sediment from all lakes was recovered with a plastic tube fitted to a Livingstone piston corer, preserving the very flocculent upper sediment. This plastic tube was extruded in the field into individually labeled Whirl-paks© at an interval of 0.25 cm for Soldier Lake and Stella Lake and 1.0 cm for Angel Lake and Overland Lake.

4.4.2 Laboratory Analyses and Chronological Control

All sediment cores were split, described, and imaged with the exception of Stella Lake, which was split and described. After imaging, the cores were either sectioned or sampled in the lab at intervals of 0.25 cm for Soldier Lake and Stella Lake and 1.0 cm for Angel Lake and Overland Lake. Lake productivity was estimate using loss-on-ignition (LOI). LOI was conducted by drying and then burning a known fraction of sediment at 100°C and 550°C, respectively, following the approach outlined by Heiri et al. (2001).
Age control was established by the use of radiocarbon dating of twigs, needles, charcoal, pollen, and woody debris preserved in the core. All radiocarbon dates were measured using AMS at either the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) (Woods Hole, Massachusetts) or Beta Analytic (Miami, FL). CALIB version 6.1.0 was used to convert radiocarbon dates ($^{14}$C yr BP) to calibrated ages before AD 1950 (cal yr BP) (Reimer et al., 2009). The age-depth models were constructed using the freely available R code package BACON (Bayesian Accumulation Model) developed by Blaauw and Christen (2011). The BACON 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) of sedimentation rates for Angel, Overland, and Stella lakes, with a mean of 20 yr cm^{-1}, 40 yr cm^{-1}, and 20 yr cm^{-1}, respectively. Soldier Lake, being the oldest lake in the study assumed a gamma distribution (shape = 2) of sedimentation rates with a mean of 45 yr cm^{-1}. The models also included the prior condition that the surface of each core was prescribed to represent the year of core acquisition. This provides a goodness-of-fit for each depth with the age reported as calibrated ages (cal yr BP).

4.4.3 Chironomid Analysis

Chironomid analysis followed (Walker, 2001). A known volume of wet sediment (minimum 0.25 mL) was deflocculated in a 10% KOH solution, heated at 30°C for approximately 30 minutes. This was then washed with distilled water, passed through a
sieve with a 95 µm mesh and backwashed into a beaker. The samples were then examined under a Zeiss Stemi 2000-C Stereo microscope in a Bogorov plankton counting tray. The head capsules are removed from the tray with a pair of fine tipped tweezers and placed in a drop of distilled water. After drying, the cover slips were permanently mounted in Entellan®. Identification of the chironomid remains is conducted under 400× magnification and is based on Wiederholm (1983), Brooks et al. (2007), and an extensive reference collection housed at The Ohio State University.

4.4.4 Statistical Analyses

The chironomid percentage diagrams were plotted using C2 (Juggins, 2003) and were 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 H.J.B Birks, unpublished program). A form of indirect gradient 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 all lakes.
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 of the 20\textsuperscript{th} century (Reinemann et al., \textit{under review}, Porinchu et al., 2010) and the mid-Holocene (Reinemann et al., 2009).

4.5 Results

4.5.1 Dating and Age-depth Models

Radiocarbon dates were initially obtained on terrestrial plant macrofossils extracted from the sediment cores. However, an insufficient number of plant macrofossils were available in Soldier Lake sediment core, so pollen concentrates isolated from two 5-cm sections centered at 300 cm and 400 cm were used to obtain additional AMS radiocarbon dates for Soldier Lake. The number of AMS radiocarbon dates varied amongst the sites with between four and eight dates obtained for each record. The chronologies and age-depth models are presented in Table 4.1 and Figure 4.2. The sediment sequences extracted from all the study sites extend through the mid-Holocene. The Angel Lake record extends to roughly 7500 cal yr BP, with the Mazama ash, which is present in the basal portion of the core, utilized as an age-control point in the BACON program. The Overland Lake record spans the last 14,000 cal yr BP, with the Mazama ash layer present at 326 cm depth and utilized as an additional age-control point. The longest record, recovered from Soldier Lake, spans 24,000 cal yr BP and utilizes a layer
at 198 cm identified as Mazama ash in the age-depth model. The Stella Lake sediment record extends to roughly 7,000 cal yr BP. The varying ages of all four lakes, have led to the decision to limit the results and discussion to the common time interval captured by all lakes: 7,000 cal yr BP to the present.

4.5.2 Loss-on-ignition

Loss-on-ignition (LOI) varies between 5% in the basal section of all the cores and 50% in the uppermost sediment of Soldier and Stella lakes (Figure 4.3). The catchment area and surface lake area data, presented in Table 4.2, indicate that the study lakes are characterized by relatively small catchment areas, an important aspect to consider when comparing the results of LOI analyses. Stella Lake had the highest overall LOI values, averaging approximately 30% through much of the Holocene. Angel Lake, Overland Lake, and Soldier Lake had LOI values that were comparable to one another averaging approximately 15% through the Holocene. All lakes experienced an increasing trend in LOI starting from 7000 cal yr BP to the present (Figure 4.3). However, Stella, Overland, and Soldier lakes experienced a dramatic increase during the last 500 years, with values increasing between two and four times their Holocene average. Angel Lake does not exhibit this recent increase in LOI; however, there appears to be a step-change in LOI at Angel and Soldier lakes between 2500 and 3000 cal yr BP.

4.5.3 Holocene chironomid stratigraphies

Sub-fossil midge stratigraphies are presented in Figures 4.4a – 4.4d.
4.5.3.1 Angel Lake

Angel Lake had the most diversity of any of the lakes in this study with a total of 27 identifiable midge taxa. Taxon richness for Angel Lake varied between nine and eighteen. The assemblages were split into five significant zones: AL-I (7000-3100 cal yr BP), AL-II (3100-2200 cal yr BP), AL-III (2200-800 cal yr BP), AL-IV (800-150 cal yr BP), and AL-V (150 cal yr BP to surface). Zone AL-I spans roughly half the core and is comprised of mostly Micropsectra, Cladopelma, Psectrocladius semicirculatus/sordidellus, Pentaneurini, Tanytarsus indeterminable, and Procladius. Lesser amounts of Limnophyes/Paralimnophyes, Cricotopus/Orthocladius, and Corynoneura/Thienemanniella are present in AL-I as well. In Zone AL-II Cladotanytarsus mancus group, Heterotrissocladius and Chironomus increase in relative abundance with the latter two taxa reaching core maxima of ~10 and ~25 %, respectively. Micropsectra’s relative abundance is greatly reduced in this zone and is nearly extirpated from the core. An abrupt shift in community composition occurs in Zone AL-III with the appearance and sharp increase of Tanytarsus type G, Tanytarsus type B, and Polypedilum. Chironomus declines with the relative abundance of C. mancus group remaining fairly constant at ~20% in AL-III. Zone AL-IV is dominated by Tanytarsus type G, Tanytarsus type B, Cladopelma, Psectrocladius semicirculatus/sordidellus, and Procladius. Also of note in AL-IV, is Cricotopus/Orthocladius reaching a core maximum of ~12%. The uppermost three samples, covering the last 200 years and comprising Zone AL-V, are distinguished by the dominance of Dicrotendipes, Tanytarsus indeterminable, Tanytarsus type G and Cladopelma, all of which with the exception of Cladopelma,
exhibit core maxima. Head capsule concentration also varied throughout the core with an average concentration of approximately 100 head capsules mL\(^{-1}\) with a core maximum of 250 head capsules mL\(^{-1}\) occurring at approximately 3500 cal yr BP.

4.5.3.2 Soldier Lake

The Soldier Lake midge stratigraphy contained a total of 18 midge taxa, with taxon richness varying from six to fourteen. During the interval of interest 7,000 cal yr BP to the present the midge stratigraphy was split into three zones: SLD-III (6200-5200 cal yr BP), SLD-IV (5200-500 cal yr BP), and SLD-V (500 cal yr BP to surface). The principal midge taxon in SLD-III is *Dicrotendipes*, which reaches a core maximum. Taxa such as *P. semicirculatus/sordidellus, Tanytarsus* type G, and *Tanytarsus* type B, which dominate deeper in the core, decrease to values below 5% relative abundance in SLD-III. SLD-IV, which spans the interval between approximately 5200 year BP and 300 yr BP, is characterized by constant relative abundances of *Procladius, Dicrotendipes, Tanytarsus* indeterminable, *Tanytarsus* type G, *Tanytarsus* type B. *Tanytarsus* Type H exhibits to small peaks in abundance in SLD-IV. *Cladopelma* and *Micropsectra* reach a core maximum in SLD-IV, with *Micropsectra* existing only in Zone SLD-IV and SLD-III. The uppermost zone, SLD-V, exhibits an increase in *Dicrotendipes, Tanytarsus* indeterminable, and *C. mancus* group with the latter reaching a core maximum in the surface sample. *Tanytarsus* type B and *Procladius* are nearly extirpated from the lake in uppermost sediment. Head capsule concentrations in Soldier Lake are the highest of any of the lakes in this study, remaining fairly constant around 500 head capsules mL\(^{-1}\), with
the exception of a few samples where head capsule concentrations increased to ~ 3000 head capsules mL⁻¹.

4.5.3.3 Overland Lake

Overland Lake is the least diverse of all the lakes in this study with only 16 identifiable taxa. The midge community is dominated by a few taxa with only four of the sixteen taxa achieving a relative abundance of >5% in any given sample. Taxon richness at Overland Lake was extremely low and varied between two and nine identifiable taxa per sample. Midge community composition remained stable during the interval of interest, resulting in no significant zones being identified in 7,000 cal yr BP to the present interval. If a longer interval is examined, the lake was split into two significant zones: OVR-I (13600-9250 cal yr BP; post-glacial) and OVR-II (9250 cal y BP to present; Holocene). Zone OVR-II is dominated by only two taxa: Sergentia (~75%) and Procladius (~20%). Of note is the slight increase in taxon richness in the upper sediment samples with P. semicirculatus/sordidellus, Micropsectra, Pentaneurini, and Cricotopus/Orthocladius increasing in relative abundance to approximately 5-10%. Head capsule concentrations in Overland Lake remained fairly constant around 200 head capsules mL⁻¹ through the last 7000 cal yr BP.

4.5.3.4 Stella Lake

Stella Lake contained 12 identifiable midge taxa and the assemblages were split into seven zones: SL-I (7000-6850 cal yr BP), SL-II (6850-6650 cal yr BP), SL-III (6650-3700 cal yr BP), SL-IV (3700-1450 cal yr BP), SL-V (1450-650 cal yr BP), SL-VI (650-
360 cal yr BP), SL-VII (360 cal yr BP to surface). The midge community present in Zone SL-I is dominated by *C. mancus* group (~30%) and *Tanytarsus* indeterminable (~25%). An abrupt shift in community composition occurs in Zone SL-II with the contribution of *C. mancus* group and *Tanytarsus* indeterminable decreasing and a large increase in *Chironomus* (~55%) and *P. semicirculatus/sordidellus* (~40%) occurring. It is notable that the abundance of *Chironomus* in Zone SL-II is three times greater than its relative abundance in the remainder of the core. The midge community present in Zone SL-III is characterized by high relative abundances of *Chironomus, P. semicirculatus/sordidellus, C. mancus* group, and *Tanytarsus* indeterminable. This zone is also characterized by the appearance of *Corynoneura/Thienemanniella*, which reaches a core maximum of ~10% at 5500 cal yr BP, and a slight increase in *Procladius*. Zone SL-IV is characterized by a decrease in the relative abundance of *Chironomus* and *P. semicirculatus/sordidellus* to between 5% and 10%. This zone is also characterized by the presence of abundant subfossil remains belonging to *C. mancus* group (30–40%). A large increase in *P. semicirculatus/sordidellus* and the disappearance of *C. mancus* group occur in Zone SL-V. Zone SL-V also exhibits a smaller peak in both *Corynoneura/Thienemanniella* and *Pentaneurini*. The midge community then observes another dramatic change in taxa in Zone SL-VI, with *P. semicirculatus/sordidellus*, and *Tanytarsus* indeterminable decreasing in the core and the rebounding of *C. mancus* group to ~50%. The uppermost zone, SL-VII, is dominated by *Tanytarsus* indeterminable and *P. semicirculatus/sordidellus*, with lower amounts of *Procladius, Chironomus* and *Tanytarsus* type H also present. Head capsule concentration varies throughout the core.
between 50 and 300 head capsules mL\(^{-1}\), with the exception of zones SL-V and SL-VI, where the concentrations spike to between 400 and 800 head capsules mL\(^{-1}\). Taxonomic richness varies throughout the core, with samples consisting of between four and eleven extant taxa.

4.5.4 Indirect gradient analysis

A form of indirect gradient analysis, DCA, applied to the subfossil midge stratigraphies reveals that all four of the sites were characterized by a relatively small amount of compositional turnover during the mid- to late-Holocene (Figure 4.5). However, three of the sites, Angel, Soldier, and Stella lakes, experience a large amount of compositional turnover during the last 2500 years. The striking feature of the ordination analyses is the unidirectional change in midge community composition that begins at 1000 cal yr BP at Stella Lake and at 2500 cal yr BP at Soldier and Angel lakes. Overland Lake exhibits very little species turnover throughout the last 6000 years. Unlike Angel, Soldier, and Stella lakes, Overland Lake experiences a large degree of compositional turnover during the early Holocene.

4.5.5 Holocene inferred temperature reconstructions

The taxa present are well-represented and characterized by the Intermountain West calibration set with almost all of the chironomid taxa comprising the chironomid stratigraphies reported in this study present in the Intermountain West training set (Porinchu et al., 2010); therefore, the MJAT reconstructions should be considered reliable. Values ranging between 2 and 13 for Hill's N2 diversity index (Hill, 1973)
provide added support that the quantitative chironomid-based MJAT reconstructions can be considered reliable (Birks, 1998); although, it is important to note that some key taxa are not well constrained by the existing Intermountain West training set. These taxa include: *Tanytarsus* type B, *Tanytarsus* type K, *Trissocladius, Psctrocladius septentrionalis, Glyptotendipes and Smittia/Psuedosmittia* The chironomid-based temperature reconstructions for Angel Lake, Soldier Lake, Overland Lake and Stella Lake are presented in Figure 4.5.

The reconstructions suggest that the mid-Holocene is relatively stable in terms of temperature although there is large sample-to-sample variability. One of the most striking features of the chironomid-based MJAT inferences for all four lakes is the lack of a clear HTM signal amongst the sites. In addition, the response of the midge communities during the last two millennia suggests the existence of a north-south temperature gradient. For example the southernmost sites, Stella Lake and Overland Lake, exhibit increased MJAT during the last two millennia; whereas, the northern sites, Angel Lake and Soldier Lake, are characterized by a trend of decreasing MJAT during the same interval. The Holocene average MJAT for Angel Lake = 11.6°C; Soldier Lake =11.1°C; Overland Lake = 8.8°C and; Stella Lake = 10.7°C. The range in chironomid-inferred MJAT for the lakes is: Angel Lake = 2.5°C; Soldier Lake =1.8°C; Overland Lake = 3.6°C and; Stella Lake = 3.2°C. The sample-specific error (SSE) estimates associated with the MJAT inferences varied between 1.0°C and 2.1°C, for all the lakes with the exception of Overland. Overland exhibits higher values of SSE (~1.3°C- 2.4°C) because of its extremely low diversity and the existence of a non-analogue situation. Angel Lake, Soldier Lake, and
Stella Lake experience their highest chironomid-inferred MJAT during the last 1,000 years. A LOWESS smoother (span = 0.2) was applied to the reconstructions highlights the main trends in MJAT over the entire record (Figure 4.6).

A plot of deviations of MJAT from the long-term average for all the lakes for the last 1,000 years is depicted in Figure 4.7. Angel Lake and Soldier Lake exhibit similar temperature trends. Post-500 cal yr BP, Angel and Soldier lakes experience negative departures from the long-term mean temperature. Here fluctuations in the midge community suggest that much of the mid- to late Holocene was characterized by limited temperature variability. Overland Lake experiences below average temperatures during the first 4,000 years of the record and above average temperatures during the last 4,000 years. The anomaly values for Stella Lake are notable. The mid-Holocene at Stella Lake is characterized temperatures above the long-term mean, reaching a local maximum of 0.5°C above the mean at roughly 5200 cal yr BP. This maxima is followed by a decreasing trend to 1.2°C below the mean at 2200 cal yr BP. Stella Lake then experiences an undulating temperature trend during the last 2,000 years, reaching a maximum at 1100 cal yr BP and during the last 100 years, with a negative departure to 1.0°C below the mean occurring at approximately 500 cal yr BP.

4.6 Discussion

Velle et al. (2010) point out that many factors affect the reliability of chironomid-based reconstructions, including: (1) the representativeness of a single surface sample of the spatial heterogeneity of the distribution of chironomids within a lake, (2) the taxonomic resolution of the analysis, (3) the robustness of the age-depth model, (4) the
choice of numerical model, and (5) the nature of the interactions between the environment and the chironomid communities. This multi-site investigation of the response of midge to Holocene climate and environmental change enables a detailed assessment of the degree to which the factors outlined in Velle et al. (2010) have influenced chironomid communities in alpine and sub-alpine lakes in the central Great Basin. The discussion is structured into five sections. The first four sections discuss each of the lakes individually providing a detailed examination of the robustness and potential drawbacks associated with each temperature reconstruction. The fifth section concludes with a discussion of the role of additional variables that might offer a more robust reconstruction of Holocene temperatures changes.

4.6.1 Angel Lake

The LOI profile for Angel Lake does not correspond strongly to the LOI profiles for the other sites in this study (Figure 4.3) or other lakes in this region (Porinchu et al., 2010; Reinemann in prep), all of which are characterized by sharp increases in organic content in last 500 years. The LOI values in the upper sediment at Angel Lake may have been affected by a dam built during the early 20th century to increase Angel Lake’s level and to provide irrigation storage. Raising the lake level of Angel Lake would alter the surface area to volume ratio, likely influencing the relative input of minerogenic material and could account for muted response of LOI observed at Angel Lake (Shuman, 2003). The existence of a distinct and statistically significant zone (AL-V), which spans the last ~100 years, indicates that the increase in volume and lake depth that resulted from the construction of the dam likely influence midge community composition. A notable
increase in *Dicrotendipes*, a taxa occurring prevalently in the littoral environments (Brooks et al., 2007), characterizes zone AL-V. *Dicrotendipes* is also associated with macrophytes (Brooks et al., 2007), indicating that the change in lake level post-AD 1920 may have altered food availability and changed the relationship between chironomid assemblages and temperatures, resulting the apparent decrease in MJAT during the recent century (Figure 4.6 & 4.7).

The midge community in Angel Lake is the most taxonomically diverse of the study sites. The presence of an active inflowing stream on the west side of the lake close to the coring location may account for this high diversity. The presence of *Simuliidae* (Black fly) remains in the uppermost Angel Lake sediment is suggestive of the potential influence of the stream on the Angel Lake midge community. Angel Lake is characterized by a large unidirectional shift in the chironomid assemblage, as indicated by the DCA (Figure 4.5) and the zonation (Figure 4.4a). This shift appears to be largely driven by the replacement of *Micropsectra* by *Tanytarsus* type G & *Tanytarsus* type B that occurs at 2000 cal yr BP. The head capsules of *Tanytarsus* type G & *Tanytarsus* type B are very similar, leading to the possibility that these two taxa are in fact morphotypes belonging to the same genus. *Micropsectra, Tanytarsus* type G & *Tanytarsus* type B all belong to the tribe Tanytarsini, a tribe which would benefit from enhanced taxonomic resolution (see section 4.6.6)(Velle et al., 2010). Factors such as changes in lake level, stream input and habitat and food availability may override the influence of recent climate change on midge community composition and confound attempts to develop meaningful chironomid-based temperature reconstructions for Angel Lake based on the
recently deposited sediment. Therefore, the reconstruction of MJAT spanning the 20th century for this lake should be interpreted with caution; however, the remainder of the record should be considered robust. Significance testing outlined by Telford and Birks (2011) resulted in a $p$-value of 0.249. The nearby presence of Smith Lake, a lake with similar characteristics to Angel Lake, provides the potential for an interesting comparison study.

4.6.2 Soldier Lake

Soldier Lake’s MJAT reconstruction is hampered by several factors, (1) the low resolution of samples taken for chironomid analysis, (2) the number of AMS $^{14}$C dates obtained in the core coupled with the extremely long age of the core, and (3) the lake basin morphology. However, significance testing outlined by Telford and Birks (2011) resulted in a $p$-value of 0.149. The chronology for Soldier Lake is not as robust as the chronologies developed for the other study sites. The Soldier Lake chronology is based, in part, on a limited number of AMS $^{14}$C dates obtained on terrestrial macrofossils due to the lack of dateable material in the core. Bulk sediment was not dated because of the large uncertainties associated with dating this material (MacDonald et al., 1991). The bottom two dates were derived from pollen that was concentrated from 5 cm thick sections of sediment. Additional age control would have required consuming more of the lowermost 2 meters of sediment and would have limited the material that would be available for additional analyses. Although a Bayesian approach was used to model the age-depth relationship (Table 4.1 and Figure 4.2), large uncertainties still remain for the portion of the core spanning the last 9000 years, which is constrained by two radiocarbon
dates and the Mazama tephra. Greater chronological constraint is required if we are to relate changes in midge community composition and the associated MJAT reconstruction to regional records of climate and environmental change.

Lake basin morphology has been identified as a factor in influencing chironomid-based temperature reconstructions (Kurek and Cwynar, 2009a, 2009b; Cwynar et al., 2012). The midge community at Soldier Lake may be greatly influenced by lake level fluctuations. A large shallow (<1m) shelf is located on the western side of Soldier Lake, with a deep pool (3.5 m) located near the eastern margin of the lake (Figure 4.8). The sediment core analyzed for this study was taken from the deepest portion of the lake, as is the standard approach in paleolimnology. *Dicrotendipes*, which is commonly associated with the littoral zone of lakes, is a large component of the chironomid community in Soldier Lake varying between 20% and 50%. The changes in the relative abundance of *Dicrotendipes* could be driven by slight changes in effective moisture that, due to Soldier Lake’s unique basin morphology, can lead to notable fluctuations in lake levels and corresponding changes in chironomid community composition. For example, a small increase in precipitation and thus lake level may expose a large expanse of littoral habitat that would be suitable for taxa such as *Dicrotendipes*. Conversely, a decrease in precipitation would increase the relative amount of benthic habitat, likely reducing the influence of temperature on the midge community (Kurek and Cwynar, 2009a, 2009b).

4.6.3 Overland Lake

Overland Lake is two to four times deeper than the other lakes in this study. The midge community at Overland Lake is notable for its extremely low chironomid
diversity. The sub-fossil chironomid assemblages in Overland Lake are dominated by two taxa: Procladius comprises between 10% and 30% of the midge community and Sergentia comprises the other 90% to 70% (Figure 4.4c). These two taxa are commonly found in the profundal zone of deep lakes (Brooks et al., 2007). Procladius is also typically the last species to survive periods of anoxia in a lake (Brooks et al., 2007). The low taxonomic diversity and the limited faunal turnover that characterizes the midge community during the last 7000 years gives rise to a unique non-analogue condition for Overland Lake. The maximum relative abundance of Sergentia in any of the lakes in the Intermountain West training set is approximately 28% (Porinchu et al., 2010). The numerical model we have chosen usually performs well in non-analogue situations Birks (1998); however, the existence of a non-analogue situation for almost all of the samples in the record suggests that the chironomid-inferred MJAT reconstruction cannot be considered robust. Significance testing outlined by Telford and Birks (2011) reaffirms this result (p-value of 0.23). In addition, fluctuations in lake depth, oxygen concentration and possibly even the length of ice-free season may have influenced midge community composition at Overland Lake through the Holocene (Reinemann et al., 2009; Brooks et al., 2012).

4.6.4 Stella Lake

Stella Lake has the most robust temperature reconstruction of all four lakes in this study. The chironomid-based MJAT estimates for Stella Lake can be considered robust because: (1) Stella Lake has the most tightly constrained chronology (Table 4.1 & Figure 4.2), (2) the WA-PLS model chosen to reconstruct temperature usually performs the best
with noisy, species-rich compositional data with many zero values (Birks, 1998), and (3) the influence of confounding environmental factors appear to be limited at Stella Lake throughout the Holocene. The robustness of the Stella Lake reconstruction is also substantiated by significance testing outlined by Telford and Birks (2011), resulting in a $p$-value of 0.001.

The peak in mid-Holocene warmth at Stella Lake (~5,500 cal yr BP) occurs a little earlier than the timing of the peak identified in the North American pollen-based temperature reconstruction which occurs at ~4,000 cal yr BP) (Viau et al., 2006) (Figure 4.9). The discrepancy in timing of mid-Holocene warmth most likely results from the varying temporal and spatial resolution of Stella Lake (sub-centennial, regional) and the pollen-based synthesis (millennial, continental). The Pyramid Lake record (Mensing et al., 2004), suggests that the mid-Holocene experienced extended intervals of severe drought, as indicated by large decreases in the ratio of Artemisia to Chenopodiaceae. A drier mid-Holocene for the Great Basin is also confirmed in lake and marsh records, reviewed in Tausch et al. (2004). The Stella Lake MJAT reconstruction suggests that the interval of decreased effective moisture during the mid-Holocene corresponds to a period of above average summer temperatures, with the elevated temperatures exacerbating regional aridity. It has been suggested that the increased aridity that characterizes the Great Basin during the mid-Holocene resulted from a change in the tropical Pacific sea surface temperature (SSTs) and a poleward shift in the Pacific High, which steered storm tracks on a more northerly trajectory (Harrison et al., 2003; Cook et al., 2004; Seager et al., 2007; Woodhouse et al., 2009; Burgman et al., 2010). Peak Holocene warmth at
approximately 5500 cal yr BP is followed by a slow downward trend in chironomid-inferred temperature at Stella Lake and in the North American pollen record through the mid- to late-Holocene, corresponding to decreased summer insolation (Figure 4.9). For a more detailed examination of the last 2000 years at Stella Lake the readers are directed to (Chapter 3).

4.6.5 Perspective on Non-consensus Reconstructions

The large degree of variability among the chironomid-inferred reconstructions developed in this study has highlighted the importance of examining the potential influence of factors other than air or water temperature on midge community composition during the Holocene. In nearly all midge calibration sets some measure of temperature is usually identified as one of the variables that can account for a large, statistically significant amount of variance in the distribution of midges and as such is likely to be utilized to develop a quantitative inference model (Walker et al., 1997; Brooks and Birks, 2000; Kurek et al., 2004; Larocque and Hall, 2004; Velle et al., 2005; Barley et al., 2006; Porinchu et al., 2009, 2009; Seppä et al., 2009; Luoto et al., 2010). The role and significance of additional environmental variables in driving the modern distribution of midges has been discussed since the beginning of quantitative midge-based paleolimnology (Walker et al., 1991, 1992; Hann et al., 1992). The influence of these variables, which include, lake depth, oxygen concentration, nutrient loading, on midge community composition is being actively debated today (Velle et al., 2010, 2012; Brooks et al., 2012; Eggermont and Heiri, 2012).
As Brooks et al. (2012) and Velle et al. (2012) discuss, the taxonomic resolution of sub-fossil midge analysis can influence chironomid-based temperature reconstructions. Sub-fossil midges are typically identified to the genus and in some cases tribe or sub-tribe. The lower the taxonomic resolution of the analysis the greater the likelihood that important ecological and paleoecological information is being lost. However, studies conducted with very high taxonomic resolution may result in the introduction of error due to misidentification or inconsistent identification (see Walker, 2001; Velle et al., 2010, Figure 2). Brooks et al. (2012) argued that the identification of the subfossil chironomid head capsules in both the training sets and down core assemblages needs to be undertaken at the highest taxonomic resolution possible because the knowledge gained from increased resolution outweighs the potential drawbacks associated with misidentification and typically results in more robust chironomid-based temperature reconstructions. In this study, the presence of Tanytarsini, a tribe known to have many species that are not easily to distinguish because of the limited diagnostic detail preserved on the subfossil remains, may account for the poor correspondence between the MJAT reconstructions.

If one is attempting to develop a regional consensus reconstruction careful site selection is required. Specifically, in arid and semi-arid environments, such as those that characterize much of the Great Basin, freshwater lakes are typically only found in the upper reaches of a drainage basin near the headwalls of catchments. From the results of this study it is clear that a lake should not be overly deep to minimize the effect on the chironomid community, especially if attempting to solely develop air temperature reconstructions. For example, the midge communities in Overland Lake are characterized
by low taxonomic diversity and are most likely responding to lake depth and the possibility for cold water pooling in the profundal of the lake. A more detailed study of the thermal characteristics of a potential study-site would be beneficial before selecting it for use in a long-term temperature reconstruction (Smol and Last, 2001). In addition, a careful bathymetric survey of the lake would be useful in identifying any potential problems associated with habitat availability and the focusing of head capsules into the deepest portion of the lake, e.g. Soldier Lake. It is clear from this study that incorporating multiple sites (and multiple proxies) provides much greater insight into regional climate variability (Velle et al., 2005). Multi-site, multi-proxy studies will ultimately lead to a more thorough examination of the controlling variables on chironomid communities in the region of interest. The additional knowledge gained from any multi-site, multi-proxy study allows a researcher to specify the certainty of each record individually and comment on the confidence of any regional synthesis.

4.7 Conclusion

In this study we present quantitative records of MJAT fluctuations spanning the last 7,000 years for four sub-alpine and alpine lakes in the central Great Basin of the United States. The Stella Lake reconstruction, which provides the most robust MJAT inferences, indicates that the MJAT characterizing the southern portion of the study transect at approximately 5500 cal yr BP is approximately 0.2°C higher than the long-term Holocene average. However, the quantitative temperature reconstructions developed in this study also reveal notable site-specific differences in the response of midge communities to Holocene environmental change. This study highlights the unmistakable
need for careful site selection to minimize the influences of factors other than temperatures (the environmental variable of interest) that could have an influence on the chironomid community assemblages. At the same time, it provides a set of criteria for site selection in long-term temperature reconstructions.
4.8 References


Luoto, T.P., Kultti, S., Nevalainen, L., Sarmaja-Korjonen, K., 2010. Temperature and effective moisture variability in southern Finland during the Holocene quantified with


Reinemann, S.A., Porinchu, D.F., Mark, B.G., under review. Regional Climate Change Evidenced by Recent Shifts in Chironomid Community Composition in Sub-alpine
and Alpine Lakes in the Great Basin of the United States. Arctic, Antarctic, and Alpine Research.


Thompson, R.S., Anderson, K.H., 2000. Biomes of western North America at 18,000, 6000 and 0 C-14 yr BP reconstructed from pollen and packrat midden data. Journal of
Biogeography 27, 555–584.


Wanner, H., Beer, J., Butikofer, J., Crowley, T.J., Cubasch, U., Fluckiger, J., Goosse, H., Grosjean, M., Joos, F., Kaplan, J.O., Kuttel, M., Muller, S.A., Prentice, I.C., Solomina,


# 4.9 Tables

<table>
<thead>
<tr>
<th>Lake</th>
<th>Lab Code</th>
<th>Depth in core (cm)</th>
<th>Material</th>
<th>$^{14}$C yr BP</th>
<th>± Age (cal yr BP) 2σ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overland</td>
<td>OS-78273</td>
<td>9</td>
<td>conifer needle</td>
<td>1290</td>
<td>1178-1283</td>
</tr>
<tr>
<td>Overland</td>
<td>OS-78274</td>
<td>55</td>
<td>wood</td>
<td>2250</td>
<td>2158-2340</td>
</tr>
<tr>
<td>Overland</td>
<td>OS-78275</td>
<td>131</td>
<td>twig</td>
<td>3030</td>
<td>3084-3345</td>
</tr>
<tr>
<td>Overland</td>
<td>OS-78276</td>
<td>247</td>
<td>twig</td>
<td>5500</td>
<td>6216-6395</td>
</tr>
<tr>
<td>Overland</td>
<td>OS-78277</td>
<td>333</td>
<td>twig</td>
<td>8200</td>
<td>9030-9270</td>
</tr>
<tr>
<td>Overland</td>
<td>OS-78278</td>
<td>414</td>
<td>twig</td>
<td>11700</td>
<td>13400-13716</td>
</tr>
<tr>
<td>Stella</td>
<td>OS-65913</td>
<td>33</td>
<td>Conifer Needle</td>
<td>185</td>
<td>83-300</td>
</tr>
<tr>
<td>Stella</td>
<td>Beta-11919</td>
<td>51</td>
<td>Conifer Needle</td>
<td>360</td>
<td>319-495</td>
</tr>
<tr>
<td>Stella</td>
<td>Beta-11920</td>
<td>60.5</td>
<td>Bark Fragment</td>
<td>420</td>
<td>464-514</td>
</tr>
<tr>
<td>Stella</td>
<td>Beta-262566</td>
<td>70.25</td>
<td>Conifer Needle</td>
<td>1250</td>
<td>1076-1276</td>
</tr>
<tr>
<td>Stella</td>
<td>Beta-262567</td>
<td>77.5</td>
<td>Conifer Needle</td>
<td>1640</td>
<td>1373-1711</td>
</tr>
<tr>
<td>Stella</td>
<td>OS-64648</td>
<td>115</td>
<td>Twig</td>
<td>2080</td>
<td>1950-2145</td>
</tr>
<tr>
<td>Stella</td>
<td>OS-64661</td>
<td>220.5</td>
<td>Twig</td>
<td>3920</td>
<td>4242-4496</td>
</tr>
<tr>
<td>Stella</td>
<td>OS-64649</td>
<td>323</td>
<td>Twig</td>
<td>5970</td>
<td>6678-6902</td>
</tr>
<tr>
<td>Soldier</td>
<td>OS-92166</td>
<td>108</td>
<td>Twig</td>
<td>1560</td>
<td>1393-1523</td>
</tr>
<tr>
<td>Soldier</td>
<td>OS-92167</td>
<td>216</td>
<td>Charcoal</td>
<td>8670</td>
<td>9540-9731</td>
</tr>
<tr>
<td>Soldier</td>
<td>OS-101202</td>
<td>296</td>
<td>Pollen</td>
<td>12350</td>
<td>14039-14898</td>
</tr>
<tr>
<td>Soldier</td>
<td>OS-101153</td>
<td>396</td>
<td>Pollen</td>
<td>20600</td>
<td>24313-24953</td>
</tr>
<tr>
<td>Angel</td>
<td>OS-64609</td>
<td>43.5</td>
<td>wood</td>
<td>585</td>
<td>535-651</td>
</tr>
<tr>
<td>Angel</td>
<td>OS-105886</td>
<td>69.5</td>
<td>wood</td>
<td>710</td>
<td>569-688</td>
</tr>
<tr>
<td>Angel</td>
<td>OS-65465</td>
<td>138.5</td>
<td>wood</td>
<td>2150</td>
<td>2046-2303</td>
</tr>
<tr>
<td>Angel</td>
<td>OS-65466</td>
<td>224.5</td>
<td>wood</td>
<td>4420</td>
<td>4870-5266</td>
</tr>
<tr>
<td>Angel</td>
<td>OS-70439</td>
<td>250.5</td>
<td>wood</td>
<td>3880</td>
<td>4240-4413</td>
</tr>
<tr>
<td>Angel</td>
<td>OS-65467</td>
<td>320.5</td>
<td>wood</td>
<td>4690</td>
<td>5320-5576</td>
</tr>
<tr>
<td>Angel</td>
<td>OS-65468</td>
<td>431.5</td>
<td>wood</td>
<td>5890</td>
<td>6574-6840</td>
</tr>
</tbody>
</table>

Table 4.1 AMS $^{14}$C dates used to derive age-depth models for the study sites. The National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) (Woods Hole, Massachusetts), and Beta Analytic Inc. (Miami, Florida) provided the dates. Lab code refers to NOSAMS sample number (OS-) or the Beta Analytic sample number (Beta-).
<table>
<thead>
<tr>
<th>Lakes</th>
<th>Angel</th>
<th>Soldier</th>
<th>Overland</th>
<th>Stella</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>41.027°N</td>
<td>40.734°N</td>
<td>40.460°N</td>
<td>39.005°N</td>
</tr>
<tr>
<td>Longitude</td>
<td>115.087°W</td>
<td>115.274°W</td>
<td>115.457°W</td>
<td>114.319°W</td>
</tr>
<tr>
<td>Elevation (m)</td>
<td>2560</td>
<td>2782</td>
<td>2886</td>
<td>3175</td>
</tr>
<tr>
<td>Max Depth (m)</td>
<td>11.0</td>
<td>3.5</td>
<td>18.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Lake Area (ha)</td>
<td>4.7</td>
<td>1.9</td>
<td>4.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Catchment Area (ha)</td>
<td>157.5</td>
<td>29.7</td>
<td>54.0</td>
<td>17.0</td>
</tr>
<tr>
<td>Drainage Ratio (catchment:lake surface)</td>
<td>33.5</td>
<td>15.6</td>
<td>11.2</td>
<td>8.9</td>
</tr>
<tr>
<td>Year Cored</td>
<td>2007</td>
<td>2011</td>
<td>2009</td>
<td>2007</td>
</tr>
<tr>
<td>Core Length (m)</td>
<td>4.5</td>
<td>4.2</td>
<td>4.5</td>
<td>3.4</td>
</tr>
<tr>
<td>No. chir. Levels</td>
<td>62</td>
<td>38</td>
<td>62</td>
<td>160</td>
</tr>
<tr>
<td>Mean no. he</td>
<td>120</td>
<td>690</td>
<td>175</td>
<td>230</td>
</tr>
</tbody>
</table>

Table 4.2 Geographic co-ordinates, year of coring, total core length, the number of levels examined for chironomids, the mean number of chironomid head capsules (he) identified from each chironomid level and additional limnological characteristics for each of the study sites.
Figure 4.1 Location of study sites located in the Great Basin of western United States. The study sites are located in the East Humboldt Mountains, the Ruby Mountains or the Snake Range of Nevada. Large cities, major lakes and the boundary of Great Basin National Park is plotted for reference.
Figure 4.2 Age-depth model for the sediment cores from all lakes (grey), overlaying the calibrated distributions of individual dates (blue). Grey dots indicate the model’s 95% probability intervals as provided by the BACON routine (Blaauw and Christen, 2011).
Figure 4.3 Loss-on-Ignition (thin line) conducted at 550°C for (A) Angel Lake, (B) Soldier Lake, (C) Overland Lake, and (D) Stella Lake graphed with respect to age. LOESS smooth (thick line) with a span = 0.2.
Figure 4.4a – d Chironomid stratigraphies for Angel (a), Soldier (b), Overland (c), and (d) Stella lakes, the order is based on the lakes’ location from north to south. Taxa have been arranged according to their MJAT optima from the chironomid-based inference model, with decreasing optima temperature from left to right. Abbreviations for chironomid taxa: *Psectrocladius semi/sordi*-type = *Psectrocladius semicirculatus/sordidellus*. (continued)
4.4a (continued)
4.4b (continued)
4.4c (continued)
4.4d (continued)

[Graph showing data with depth (cm) on the x-axis and age (cal yr BP) on the y-axis.]
Figure 4.5 DCA Axis 1 plotted against age for Angel (a), Soldier (b), Overland (c), and (d) Stella lakes. Heavy solid lines represent a LOWESS smoother (span = 0.20).
Figure 4.6 Chironomid-based mean July air temperature reconstructions for Angel (a), Soldier (b), Overland (c), and (d) Stella lakes. Points represent chironomid-based MJAT inferences, with positive SSE plotted in light gray. The heavy line represents a LOWESS smoother (span = 0.20).
Figure 4.7 Deviations of the chironomid-based MJAT from the long term mean of Angel (a), Soldier (b), Overland (c), and (d) Stella lakes, ordered based on the lakes’ location from north to south. Thick line represents a LOWESS smoother (span = 0.20).
Figure 4.8 Bathymetric map of Soldier Lake.
Figure 4.9 Summary diagram of select published paleoclimate records from all lakes in this study. (a) LOESS smooth of the chironomid-inferred MJAT anomaly relative to the AD 1000 – AD 2000 year MJAT average (b) Chironomid DCA axis 1, (c) Loss-on-ignition, (d) North American pollen-based July air temperature anomaly (Viau et al., 2006), (d) pollen A/C ratio from Pyramid Lake (Mensing et al., 2004), and (e) Insolation changes at 30°N (Berger and Loutre, 1991).
Conclusion

This research project focused on reconstructing past climate and environmental conditions in the Great Basin of the United States, incorporating four specific studies. The results and conclusions are briefly reviewed below.

(1) **Investigation of the influence of pollutant loading on high elevation sub-alpine and alpine lakes in the central Great basin during the 20th and 21st centuries.**

Remote aquatic ecosystems in the central Great Basin have been affected by local, regional, and global anthropogenic pollutant loadings over the 20th century, in this order. SCPs, which varied in absolute concentration between the lakes examined in this study, nevertheless provide a consistent signal of increasing pollutant loading during the late 20th century. Peak SCP concentration, which occurred at ~ AD 1970 across the study sites, subsequently declined, most likely in response to the stricter pollution controls implemented in the United States and Europe. Mercury fluxes exhibit a slightly more complex regional signal. Two of the study sites were characterized by peak Hg flux during the early 1970’s, while the Hg flux at the remaining sites peaked in the early 20th century. All of the study lakes are characterized by a slight increase in the Hg and SCP
flux in the most recently deposited sediment. Recent work has suggested inputs from the free troposphere could be derived regionally or globally (Huang and Gustin 2012). To further understand what may be driving this recent increase in the Hg flux to the sediment, more work is needed to describe the transport of Hg and track pollution sources in this region.

(2) **Documenting the response of sub-alpine and alpine lakes in the central Great Basin to recent climate change through high resolution analyses of sediment organic content and sub-fossil midge remains.**

This study further supports earlier research from western United States and other regions, mainly Europe, documenting recent changes in midge communities in sub-alpine and alpine lakes (Battarbee et al., 2002; Solovieva et al., 2005; Porinchu et al., 2007a, 2010). Changing thermal conditions, due to radiative forcing, has been implicated in numerous studies as a driver of the observed shift in midge community composition (Solovieva et al., 2005; Porinchu et al., 2010; Larocque-Tobler et al., 2011). With a better understanding of the controls on chironomids during the instrumental interval (150 years), where comparison to independent temperature records is possible, a better understanding of the chironomid-temperature relationship can be gained (Eggermont and Heiri, 2012) and greater confidence can be placed in chironomid-based Holocene temperature reconstructions (Porinchu et al., 2007a). The results from this study further reinforce the link between climate change and midge communities, thus supporting the continued use of midges in developing longer-term paleotemperature reconstructions. This work also establishes a regional limnological baseline that will both help to identify
the degree to which aquatic ecosystems in these vulnerable regions have been or are being impacted by anthropogenic activities (Wolfe et al., 2003; Karst-Riddoch et al., 2005), and provide a long-term context to evaluate future changes in aquatic ecosystem structure and function (Swetnam et al., 1999; Smol, 2008).

(3) The application of a chironomid-based inference model for mean July air temperature (MJAT) and development of a detailed, multi-decadal scale, quantitative reconstruction of thermal conditions for Stella Lake in Great Basin National Park (GBNP) spanning the last two millennia.

The quantitative multi-decadal chironomid-based temperature reconstruction from Stella Lake provides much need insight into thermal variability in the central Great Basin for the last two millennia. The Stella Lake record established 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 supports 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., 2007b). 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.

(4) **An investigation into the changing thermal and environmental conditions at four sub-alpine to alpine lakes in the central Great Basin over the mid- to late-Holocene.**

In this study we present a detailed examination into environmental change over the course of the mid- to late-Holocene at four sub-alpine to alpine lakes in the central Great Basin of the western United States. The Stella Lake reconstruction, which provides the most robust MJAT inferences, indicates that the MJAT characterizing the southern portion of the study transect at approximately 5500 cal yr BP is approximately 0.2°C higher than the long-term Holocene average. The Angel Lake reconstruction, which provides a robust MJAT inference during the Holocene indicates that slightly elevated temperatures characterize the northern extent of the study site transect during the HTM. The qualitative description of the northern portion of the study transect reveal notable site-specific differences are responsible for the chironomid communities through the Holocene. This study highlights the unmistakable need for careful site selection to minimize the influences of factors other than temperature (the environmental variable of interest) that could have an influence on the chironomid community assemblages. At the same time, it provides a set of criteria for site selection in long-term temperature reconstructions.
References

Introduction


Pla S, Monteith D, Flower R, Rose N (2009) The recent palaeolimnology of a remote Scottish loch with special reference to the relative impacts of regional warming and


Chapter 2


Juggins, S., 2003: Program C2 Data Analysis.


Chapter 3


Christen, J.A., Fox, C., 2010. A general purpose sampling algorithm for continuous distributions (the t-walk). Bayesian Analysis International Society for Bayesian


Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., Karlen, W., 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-


Quaternary Science Reviews 30, 1272–1278.


Chapter 4


radiocarbon age calibration curves, 0-50,000 years cal BP. Radiocarbon 51, 1111–1150.


Conclusion


Proceedings of the National Academy of Sciences 107, 21283–21288.