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Evaluating Lake Response to Environmental and Climatic Change using Lake Core Records and Modeling

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EVALUATING LAKE RESPONSE TO ENVIRONMENTAL AND CLIMATIC CHANGE USING LAKE CORE RECORDS AND MODELING

by

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EVALUATING LAKE RESPONSE TO ENVIRONMENTAL AND CLIMATIC CHANGE USING LAKE CORE RECORDS AND MODELING

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This dissertation evaluates how lakes respond to changes in their environmental and climatic settings. This dissertation consists of two lake modeling projects and the environmental and paleoclimatic reconstructions of four lakes in southwestern Montana. Lakes and their associated biological communities respond to environmental and climatic change on rapid timescales. Lake modeling and lake core stratigraphies are complementary tools for exploration of how lakes and their biota respond to environmental or climatic perturbations. In one modeling approach for exploring these issues, a simple hydro-climatological lake model was developed that classifies lake sensitivity to climatic perturbations based upon lake area, catchment area, precipitation, and evapotranspiration. Using simple ratios of these commonly measured parameters the model classifies lakes into three domains: ephemeral, sensitive to vegetation change, and permanent. The lakes that plot within the sensitive to vegetation change domain should show water balance fluctuations in response to environmental change, and these lakes would make good targets for paleoclimatic studies.

Diatom records from four lakes, Crevice Lake, Foy Lake, Morrison Lake, and Reservoir Lake, in southwestern Montana provide late-Holocene (past 3000 years) records of environmental and climatic variability. The lakes show similarities in the timing of major changes in the fossil diatom assemblages, suggesting regional climate forcings. Spectral analysis of the lake-core records suggest periodic fluctuations at spectral frequencies that are characteristic of oceanic influence on climate, such as the Atlantic Multi-decadal Oscillation and Pacific Decadal Oscillation.

The Crevice Lake core diatom record shows three distinctive diatom communities during the approximately the last 1000 years. The model DYRESM-CAEDYM was used in an inverse modeling approach to provide a means to estimate climate variables during these three stages. The model estimates of climate variables during the Medieval Period, the Little Ice Age, and the 20^{th} century, include incoming shortwave radiation, cloud cover, vapor pressure, and wind speed. The model results suggests that changes in spring seasonality, when the climate variables differ the most, is more important in affecting diatom community composition than total deviations from modern averages.

DEDICATION

I would like to dedicate this dissertation to my wonderful husband, Mike, whose support and laughter kept me sane throughout this entire process. Also, to my parents, Gary and Vicki Bracht, who have never questioned my dreams, or career choice.

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First and foremost, I would like to acknowledge and thank my advisor, Dr. Sherilyn Fritz for her all her assistance, and for putting up with my writing. I would like to thank the University of Nebraska-Lincoln Department of Geosciences and the Geological Society of America for providing funding and grant assistance. I would like to thank my committee, Dr. Kyle Hoagland, Dr. Robert Oglesby, Dr. John Lenters, and Dr. John Gates for their support and critique of my research efforts. Jeffery Stone and Karlyn Westover sparked my interest in the lake and paleoclimate realm. Without their willingness to teach and friendship, I am not sure I would be at the point I am now. Dr. Eric Grimm and Pietra Mueller cored both Reservoir and Morrison Lakes and provided assistance sampling the cores. The Yellowstone National Park Research Office, particularly Christie Hendrix and Stacey Gunther, provided assistance with field work and research permitting. Gary, Vicki, and Blake Bracht were always willing to assist in field work, regardless of how far I made them hike. I am extremely grateful to all those who helped, in a myriad of ways, to make this dream possible.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background & Scope

Water management often relies upon understanding past variability in the hydrologic balance in order to estimate current and future water supplies. Many methods exist to either monitor or understand the regional or local hydrologic balance. Among these methods are modeling and lake core proxy records.

In the western United States, arid conditions and growing populations may result in greater water demand than supply, and persistent precipitation deficits in recent years have produced severe water shortages throughout much of the region (*Christensen et al.*, 2004; *Changnon et al.*, 1991; *Hidalgo*, 1996). Understanding the natural variability of available moisture is key to management of an often sparse resource. The Rocky Mountain region has a spatially variable climate, which is the product of strong topographic gradients and the resultant differential heating of mountain slopes, diversion or concentration of winds through mountain passes, and precipitation rain shadows, amongst others (*Williams et al.*, 1996). In recent years, warmer winter and spring temperatures have affected the volume of mountain snow pack and the timing of seasonal snowmelt and runoff (*Barnett et al.*, 2005; *Mote et al.*, 2005). However, historical weather records are limited in their length and may not capture the full range of natural climate variability (*McCabe et al.*, 2008, 2004; *Stone and Fritz*, 2006).

Lakes, through sediment core records, provide several methods to reconstruct the environmental and climatic variability throughout the late-Holocene, and these records can yield important perspectives on the pattern of natural climatic variation (*Fritz*, 2008; *Fritz et al.*, 2001; *Bradley and Jones*, 1993). Multiple lake studies from a single region are preferable, because this allows comparison of the records to determine which changes result from large-scale regional forcing and which reflect only local forcings. Distinguishing between regional and local inputs is important in montane environments, as these regions exhibit a high degree of spatial heterogeniety. In this thesis four lakes from southwestern Montana provide lake core records that extend past 2500-3000 years. Diatoms are the main proxy used to reconstruct past climate, but some geochemical analyses are included, as well.

Lake core records typically provide qualitative rather than quantitative analysis of past environmental and climatic change. However, combining these records with lake models provides a method to determine the magnitude of change. In addition, hydro-climatic models may provide useful insight to the sensitivity of lakes of differing physical or hydrologic characteristics to changes in the hydrologic budget, which in turn may be useful in determining which lakes to study to reconstruct past change. Models also provide a basis for evaluating the effects of land use/vegetation change, under stationary climatic conditions, on lake depth.

The numerical lake/reservoir model, DYRESM-CAEDYM combines a variety of inputs to determine the thermodynamic, chemical, and biologic structure of the lake. By adjusting climate parameters in the model to simulate paleoclimatological conditions, it can be used as a tool to model the thermodynamic structure and to predict diatom abundances and distributions based on what we know about their ecology. By adjusting the model outputs to match the ecology of the dominant diatom species found in the sediment record, one can generate quantitative estimates of temperature, incoming solar radiation, cloud cover, precipitation, vapor pressure, and wind speed for previous climate regimes.

This dissertation attempts to evaluate lake response to climate perturbations using both modeling approaches and paleoecological data. Several questions form the framework for these studies:

1. What geographic and morphometric constraints most strongly influence the likelihood that lakes will provide highly-sensitive records of past climate?

2. What is the climatic and environmental history of southwestern Montana, based upon

cores from four lakes, and to what extent do individual lakes reflect regional versus localized influences?

3. Can lake models and lake core records be used in combination to effectively quantify climatic variables that influence diatom community composition?

1.2 Preface To Chapters

1.2.1 Chapter 2

We developed a steady-state, basin-lake water balance equation that predicts basin area to lake area ratio (A') as a function of mean annual climate, quantified by an aridity index, Φ (mean annual potential evapotranspiration to precipitation ratio). The model includes an empirical calibration parameter that reflects the influence of soils and vegetation. The model relies upon four parameters, lake area, catchment area, precipitation, and evapotranspiration to determine lake steady-state conditions. Based upon these parameters, the model separated lakes into three domains, permanent, sensitive to vegetative change, and ephemeral. Comparison of over 150 lakes, from every continent except Antarctica, to the three model domains, provides a means to compare model predicted lake conditions with actual lake conditions. The model can be used: (1) as a diagnostic tool to analyze lake response to climate change; (2) to assess environmental and anthropogenic factors leading to transient lake response; and (3) a paleoclimatic research tool to identify lakes that can provide high-resolution paleorecords of water balance.

This manuscript is part of a collaborative effort that stemmed from one of my comprehensive exam questions. Dr. Erkan Istanbullouglu designed the model, while I modified the model, collected the lake data, and applied these data to the model. I wrote the manuscript with assistance from Dr. Erkan Istanbullouglu and Dr. Sherilyn Fritz. This manuscript is currently in review in *Water Resources Research*.

1.2.2 Chapter 3

The Rocky Mountains are an important part of the hydrologic balance, in that many regions rely upon the snowmelt fed streams for urban use, agriculture, and industry (*Changnon et al.*, 1991). Climatic reconstructions from geologic and biotic archives provide a means to evaluate the natural climatic and hence hydrologic variability of this region to aid in water resource management. Lake sediment cores can provide high-resolution (sub-decadal scale) records spanning thousands of years. Diatom records from four lakes in western Montana, Crevice Lake, Foy Lake, Morrison Lake, and Reservoir Lake were used to reconstruct environmental and climatic variability of western Montana throughout the past 3000 years. Crevice Lake is within Yellowstone National Park, Foy Lake is in the Salish Mountains, while Morrison and Reservoir Lakes are within the Beaverhead Mountains. The lakes show similarity in the timing of major change in their fossil diatom assemblages at 2200-2100, 1700-1600, 1350-1200, and 800-600 cal yr BP. The 800-600 cal yr BP shift is common in North American paleoclimatic records and correlates with the onset of the Little Ice Age, a period of substantially cooler temperatures.

In this study, I counted the diatoms and made primary environmental interpretations for Crevice, Reservoir, and Morrison Lakes, while Jeffery Stone provided the diatom counts for Foy Lake and their interpretation. I carried out statistical analysis and synthesis of the diatom data and undertook primary responsibility for writing the manuscript. Dr. Sheri Fritz contributed to data interpretation and manuscript preparation. This manuscript will be submitted to either *Quaternary Research* or a journal with a similar target audience.

1.2.3 Chapter 4

Diatom lake core records provide a qualitative means to reconstruct the direction and relative magnitude of environmental and climate change. In addition to paleoclimatic reconstructions, models are an important tool for reconstructing synoptic climate change through the Holocene. The model DYRESM-CAEDYM, a coupled thermodyamic ecological model, when used with lake core records, provides one method to estimate previous climate. DYRESM-CAEDYM relies upon extensive datasets of lake temperature, chemistry, inflows, and outflows, in addition to measurements of algal concentrations. The model outputs are estimates of incoming solar radiation, cloud cover, temperature, vapor pressure, and wind speed The model was used to try to characterize these climatic characteristics during the Medieval Warm Period and Little Ice Age. In an inverse modeling approach, model parameters were adjusted to produce changes in lake thermal structure that are consistent with the distinctive diatom assemblages that are characteristic of these two intervals.

Many different people helped with the data collection of this paper. Yellowstone National Park Research Office, Christie Hendrix and Stacey Gunther, provided valuable assistance with park permits and with field data collection. I carried out all the modeling in the paper and took primary responsibility for writing the manuscript. Dr. Fritz provided valuable comments and organization that greatly improved this manuscript. Dr. John Lenters provided the thermistors and weather station equipment, provided some field assistance, and suggested exploring lake thermodynamic models. This chapter is a manuscript that will be submitted to either *Freshwater Biology* or a similar journal.

1.2.4 Chapter 5

Chapter 5 summarizes the main findings and conclusions of the preceding chapters. It also discusses potential ways to expand and build upon this dissertation.

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Chapter 2

A hydro-climatological lake classification model and its evaluation using data

Abstract

For many of the world's lakes, particularly those in remote regions, simple tools that use limited amounts of data that can be easily estimated or obtained are useful evaluating how those lakes will respond to climate change. A regional steady-state lake water balance model was developed that uses an aridity index (potential evapotranspiration to precipitation ratio, PET/P, Φ=PET/P) to estimate lake basin area to lake surface area ratio (A'), a non-dimensional lake-basin property that can be easily obtained from digital maps. In the model, lake water balance components include precipitation, lake evaporation, evapotranspiration, and runoff into the lake. Both basin runoff and evaporation are incorporated in the analytical model using an empirical equation (based on the Budyko hypothesis) that utilizes the aridity index and a free parameter often used to calibrate the impact of vegetation. Observed records of A' for lakes, as a function of their Φ, for a range of climates and vegetative conditions, were plotted and compared to a family of $A' - \Phi$ curves. Dividing the $A' - \Phi$ domain into regions of permanent, transient, and ephemeral lakes allows for comparison of model predicted lake classification with lake records. The impact of vegetation and climate change on lake persistence is also discussed. The theoretical steady state conditions are most accurate for closed basin lakes in sub-humid, semi-arid, and arid environments. The model can be used: (1) as a diagnostic tool to analyze lake response to climate change; (2) to assess environmental and anthropogenic factors leading to transient lake response; and (3) a paleoclimatic research tool, to identify lakes that can provide high-resolution paleorecords of water balance.

2.1 Introduction

Understanding the response of lakes to climate change is essential for managing water resources and associated biological communities, as well as for interpreting lacustrine records of past climate variability. Water management is an increasing concern for many regions throughout the globe (*Downey and Dinwiddie*, 1988; *Arnell*, 1999). Growing populations and over-allocation of current resources increases the need to understand natural climatic variability and its regional impacts (*Changnon et al.*, 1991; *Byrne et al.*, 1999). An increasing number of studies suggest that records that span several hundred to several thousand years are necessary to understand the full range of a climatic variability (*Cook et al.*, 2007; *Stine*, 1994). Several methods that expand the temporal framework of consideration relative to instrumental climate record rely upon lake sediment cores to reconstruct climate (*Stone and Fritz*, 2006; *Westover*, 2006; *Shapley et al.*, 2002). Throughout the paleolimnology literature, it is quite evident that climate patterns are more clearly inferred from certain lakes and other lakes provide confusing or ambiguous conclusions (*Fritz*, 2008; *George and Hurley*, 2003). Reasons vary as to why an individual lake may or may not be sensitive to climate, or which climate parameters may have the largest influence on lake response (*Stone and Fritz*, 2004; *Bracht et al.*, 2008). Several of these influences include position within the landscape, size, bathymetry, groundwater inputs, and anthropogenic influences. To overcome several of these limitations, many lake paleoclimate studies have focused on ecotones, or regions known to be sensitive to climate, but this provides little information about an individual lake's ability to provide proxy data capable of implying changes in precipitation - evaporation (P-E) (*Fritz*, 2008). Paleolimnologists have few tools to aid in choosing potential lake coring sites. Increasing the tools available for choosing lake coring sites would provide a valuable asset to paleolimnologists wishing to study climatic change.

Lake models can be used to provide insight into how lakes respond to specific aspects of climate change through quantification of the hydrologic balance (*Hostetler et al.*, 1994; *Tate et al.*, 2004). Most prior modeling studies of lacustrine hydrology considered an individual lake or small suite of lakes and their responses to changes in temperature, solar radiation, or CO_2 (*Hostetler et al.*, 2000; *Vassiljev*, 1998; *Vassiljev et al.*, 1995). However, such focused studies do not provide a large-scale picture of lake hydrologic response in relation to geographic location and climate (*Bennett et al.*, 2007; *Sass et al.*, 2008; *Vassiljev et al.*, 1995; *Webster et al.*, 2000).

We developed a steady-state, basin-lake water balance equation that predicts basin area to lake area ratio (A') as a function of mean annual climate, quantified by an aridity index, Φ (mean annual potential evapotranspiration to precipitation ratio). The model includes an empirical calibration parameter that reflects the influence of soils and vegetation. The model relies upon information that is readily available for even the most remote regions. Our approach is similar to that of *Bowler* (1981), in which a lake stability classification scheme, based upon water-balance components, was developed and implemented for Australian lakes. *Bowler* (1981) did not calculate runoff and evaporation explicitly but assigned values to these model parameters. However, in this paper we calculate runoff and evapotranspiration explicitly, using an aridity index based method that allows for climatic classification and incorporates vegetative influences.

The simple hydrologic model presented here quantitatively assesses both a lake's sensitivity to climate and its potential to preserve a complete sediment record of climate history. The model mainly has utility largely in arid, semi-arid, and sub-humid regions. The model is also useful when little hydrologic information is available for the lake, such as whether or not the lake is a closed basin, or has major groundwater fluxes or surface inflows. While the model is most useful for closed basin lakes, it may aid in the determination of whether or not a particular lake is within an enclosed basin. Within the model, vegetation is important in influencing the amount of basin runoff to the lake; therefore, we include the effects of basin vegetation within the model. Based upon the vegetation-specific, steady-state thresholds, we identify several lake categories, permanent (those that do not desiccate), sensitive to vegetative change, and ephemeral (desiccates frequently).

Using lake plotting position, we evaluate lake sensitivity, which we define as the change in Φ or A' required to change a lake's plotting position to a different category, permanent, sensitive to land use change, or ephemeral. We are also able to identify lakes whose dominant controls on lake level are climate and lake area/surface area interactions, or if other parameters are important in affecting lake level variation. This model may be useful in evaluating sites for specific hydrologic or paleoclimate questions, regional controls on lake level, or lake response to land-use change. Below, we describe the theory and how it relates to observations from 150 different lakes.

2.2 Methods

2.2.1 Analytical Model

The rate of change in the volume of a lake as a function of lake average standing water depth h_l (assuming that hdA_l/dt is negligible) can be written as the sum of water influxes as precipitation and basin runoff minus lake evaporation, as:

$$A_l \frac{dh_l}{dt} = A_l(P - E_l) + R_b A_b \tag{2.1}$$

where A_l is lake surface area, P is precipitation rate, E_l is lake evaporation rate, R_b basin runoff rate to the lake, and A_b is the area of the basin feeding the lake. Dividing both sides with A_l and using a normalized runoff area as $A' = A_b/A_l$ we can write:

$$\frac{dh_l}{dt} = (P - E_l) + R_b A' \tag{2.2}$$

Note that groundwater inflow is included in the R_b term (assuming that the groundwater basin is not significantly larger than the surface basin), but groundwater seepage and surface outflows are not included explicitly. This simplification was made due to the limited availability of lake outflow data, and so the lake model developed here is mostly relevant to closed basin lakes. Under a stationary climate, over large time scales (greater than one year), if water input to the lake is balanced by evaporation, such that $dh_l/dt = 0$, then we write lake steady-state water balance as:

$$0 = \bar{P} - \bar{E}_l + \bar{R}_b A' \tag{2.3}$$

In the equation $\bar{P}, \bar{E}$, and $\bar{R}_b$ are mean annual values of precipitation, lake evaporation, and basin runoff. Conceptually basin runoff includes any surface, subsurface, and groundwater flow contributions from the basin.

In this simplified steady-state model, we propose to estimate $\bar{R}_b$ and $\bar{E}_l$ from the Budyko hypothesis (*Budyko*, 1974). Budyko (1974) postulated that the mean annual actual evapotranspiration ($\bar{ET}_a$) of a basin asymptotically approaches the mean annual precipitation ($\bar{P}$) as the climate gets drier. The climate is represented by an aridity index, $\Phi = \bar{ET}_p/\bar{P}$, where $\bar{ET}_p$ is the maximum or potential mean annual evapotranspiration. Assuming that precipitation is in balance with runoff and actual evapotranspiration on a mean annual basis, and that inter-basin groundwater flow is negligible, basin water balance normalized with respect to precipitation becomes:

$$\frac{\bar{R}_b}{\bar{P}} + \frac{\bar{ET}_p}{\bar{P}} = 1 \tag{2.4}$$

The Budyko hypothesis suggests that,

$$\frac{\bar{ET}_a}{\bar{P}} = F(\Phi), \begin{cases} F(\Phi) \to 0, & \Phi \to 0 \\ F(\Phi) \to 1, & \Phi \to \infty \end{cases} \tag{2.5a}$$

$$\frac{\bar{R}_b}{\bar{P}}, \begin{cases} 1-F(\Phi) \to 1, & \Phi \to 0 \\ 1-F(\Phi) \to 0, & \Phi \to \infty \end{cases} \tag{2.5b}$$

where $F(\Phi)$ is an empirical function that estimates the fraction of evapotranspiration relative to precipitation. The Budyko hypothesis has been widely used as a conceptual framework for examining basin water balance in a range of climates and environmental conditions, and for developing and validating regional hydrologic models (*Milly and Dunne*, 1994; *Choudhury*, 1999; *Koster and Suarez*, 1999; *Atkinson et al.*, 2002; *Farmer et al.*, 2003; *Porporato et al.*, 2004; *Zhang et al.*, 2001, 2004, 2008). The simplistic nature of this hypothesis provides an opportunity to relate the steady-state lake water balance model to climate.

For $F(\Phi)$we use the model proposed by (*Zhang et al.*, 2001), that predicts $\bar{ET}_a/\bar{P}$

$$\frac{\bar{ET}_a}{\bar{P}} = F(\Phi) = \frac{1+w\Phi}{1+w\Phi+\Phi^{(-1)}} \tag{2.6}$$

where w is an empirical parameter used to represent the differences in land cover condition. Using the Budyko hypothesis to write (2.3) as a function of $\bar{P}$, Φ and A', we assume that lake evaporation is identical to potential evaporation used in (2.4) and approximated by $\bar{E}_l = \bar{ET}_p = \bar{P}\Phi$. Next, invoking steady-state basin water balance, $\bar{R}_b = \bar{P} - \bar{ET}_a$ and substituting $\bar{ET}_a = \bar{P}F(\Phi)$ in this equation and rearranging (2.3) becomes:

$$0 = \bar{P}(1-\Phi) + \bar{P}(1-F(\Phi))A' \tag{2.7}$$

Clearly in this form, the basin to lake area required to maintain a steady-state balance of fluxes into and out of the lake can be calculated as a function of the aridity index by solving (2.7) for A' yielding:

$$A' = \begin{cases} \frac{\Phi-1}{1-F(\Phi)} & \Phi \geq 1 \\ 0 & \Phi < 1 \end{cases} \tag{2.8}$$

Clearly, A' cannot physically equal 0, but this is given as a null value, as the model cannot estimate A' in these climates. Figure 2.1a plots equation (2.8) for two typical values of land cover conditions that can be used to evaluate the role of climate. Conceptually we consider the region bounded with the forest and bare soil lines as a range of A' required to maintain lakes in a given climate. Lakes within that region may be permanent or ephemeral, conditioned on their vegetative cover. Lakes that fall above the forest threshold line can be considered permanent, and those that fall below the lower bare soil threshold line can be considered ephemeral. Lakes that plot between the two outermost (forest and bare soil) thresholds are most sensitive to land-use change.

Note that in equation (2.8) $A'>0$, if $\Phi>1$. When $\Phi<1$, the climate is energy limited, and potential evapotranspiration falls below precipitation (Figure 2.1a). The vertical dashed line separates energy and water limited environments. In humid climates, lake formation would be closely related to availability of topographic depressions to store water, as the theory does not predict A' when $\Phi \leq 0$. Thus, lakes in energy limited regions, under a stationary climate, would be permanent, and their formation solely controlled by topography. In the water limited portion of the $A' - \Phi$ domain, plotted in Figure 1a, A' increases nonlinearly as climate becomes arid. This results from needing larger basin areas to compensate the growing evaporative demand.

Theoretically for a given vegetation type, which may be represented by a range of w

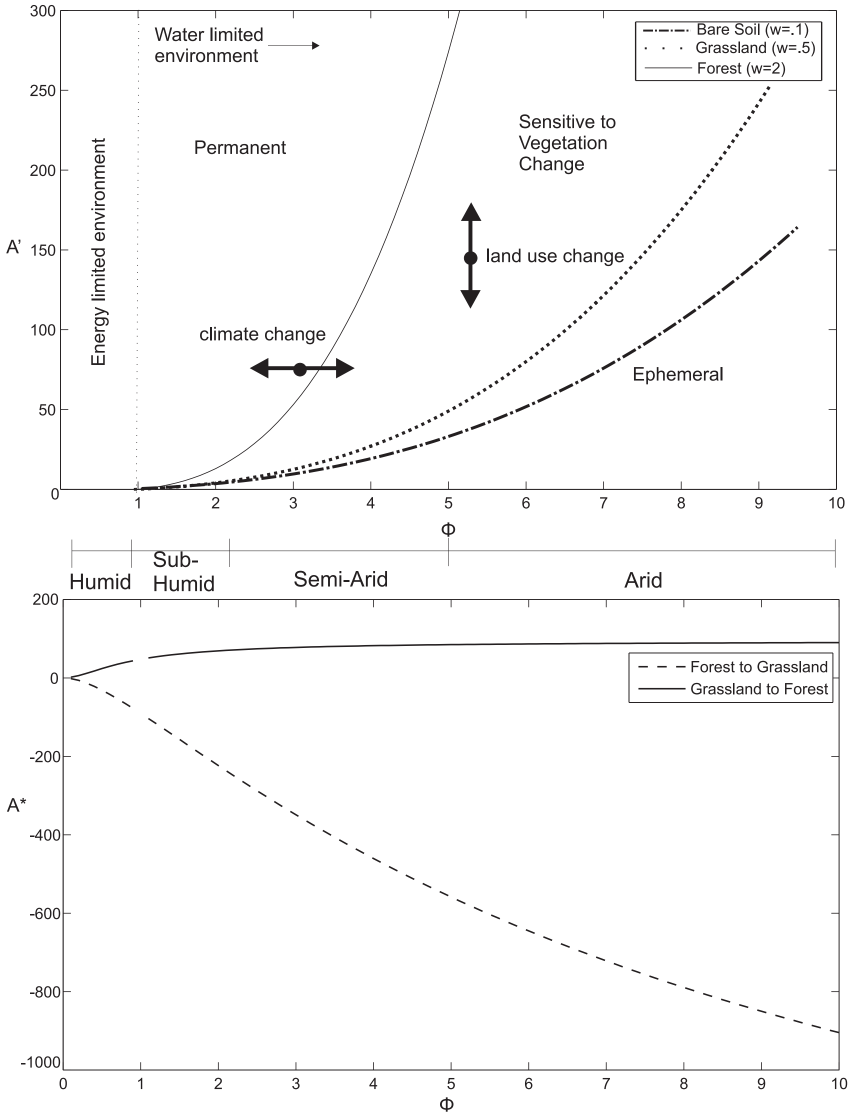

Figure 2.1: A as a function of a range of Φ values for three typical values of w representing different land cover impacts. We separated the $A-\Phi$ domain into different lake classification regions based on climate. The vertical dashed line separates the energy and water-limited environments. In humid climates, where there is more water input than energy to evaporate it ($\Phi \leq 1$), lake formation would be closely related to availability of topographic depressions to store water. Therefore for such systems A is not predicted by the theory, suggesting that any closed topographic depression could lead to lake formation. Such lakes will be permanent and remain on the landscape unless climate becomes drier. Figure 1b shows that vegetative change, in a non-transient climate, changes A', implying a change in water depth. Under constant climatic conditions, change from grassland to forest would require an increase in basin size (to compensate for increases in ET) to maintain lake level. The curves show the magnitude of change in lake area resulting from land-use change.

values, lakes that plot above the vegetation-specific $A' - \Phi$ threshold curve have larger basin areas than minimally required to satisfy evaporative water losses. We expect that the smaller the A' of a lake compared to the vegetation specific threshold lines, for a given Φ, the more frequently the lake will desiccate (or experience water losses) as a result of climate fluctuations. If a lake plots below its vegetation specific threshold, then evaporative losses are considerably larger than incoming moisture, suggesting that these lakes are continually losing volume (unless the lake is receiving inputs from other sources).

The theory can also be used to examine the impact of land-use change on lake-level. Basin vegetation, which affects evapotranspiration rates, greatly affects the amount of basin runoff that reaches the lake. Figure 2.1b illustrates the impact of land-use change on lake hydrology. The two curves are for typical values of w, forest and grassland. As expected, forested basin PET is larger than grassland PET, resulting in a greater A' requirement to maintain a lake water balance under a grassland to forest conversion. Under the same climate, a grassland basin will need a smaller A' than a forested basin. When land cover changes from grass to forest under a constant Φ, a lake would reduce its size and may even desiccate depending upon the climate aridity. Percent change in A', as a result of land-use change, can be calculated by:

$$A^{\star} = \frac{A'_{grassland} - A'_{forest}}{A'_{grassland}} * 100 \quad or \quad A^{\star} = \frac{A'_{forest} - A'_{grassland}}{A'_{forest}} * 100 \tag{2.9}$$

Interestingly, the theory predicts that land-use change would have different impacts on A' depending on climate. Vegetative conversion from grassland to forest results in greater basin PET, thus less runoff reaches the lake. In reality, increases in A' would lead to a reduction in lake level, as basin area is unlikely to change. The figure also reveals a more dramatic impact of vegetation change as climate gets drier, with a higher loss of lake surface area. While the potential outcomes of climate and land-cover changes on lake response may be explained qualitatively, our analytical model gives quantitative estimates of A' that may be used for paleoclimatic studies or lake water management.

2.2.2 Data

We use the model as a diagnostic tool to evaluate, in relation to vegetative conditions, the observed $A' - \Phi$ values of lakes globally to interpret certain lakes' sensitivity to climatic fluctuations. Lakes, over 150 globally, included in this study vary in location, surface area, volume, climate, and anthropogenic influence (Figure 2.2).

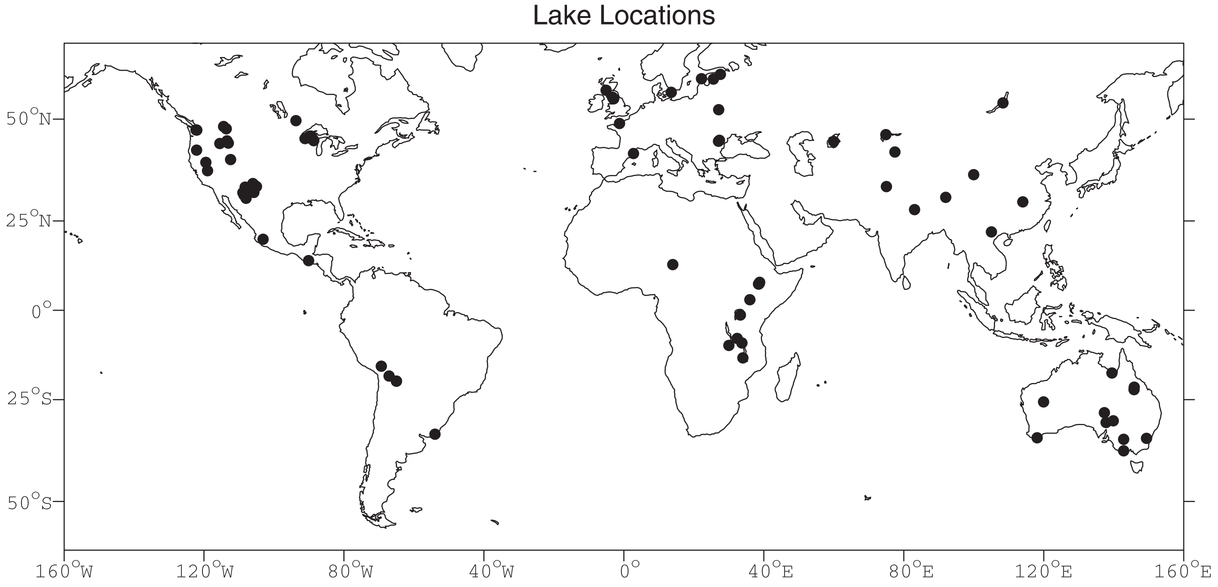

Figure 2.2: Locality map of the different lakes used in the $A' - \Phi$ threshold model. Every continent was included in the study, with the exception of Antarctica. Some geographic regions are either over or under represented in the model, resulting from data availability.

Data for lake surface area, watershed area, (potential evapotranspiration) PET, and precipitation come from a variety of sources and methods, including publications, GIS measurements of basin and lake area, and data from the International Water Management Institute (IWMI:`www.iwmi.cgiar.org`), the Northern Temperate Lakes Long Term Ecological Research (LTER:`www.lter.limnology.wisc.edu`), Experimental Lakes Area

(ELA: `www.experimentallakesarea.ca`), World Lake Database (WLD: `www.ilec.or.jp`), and the National Oceanographic and Atmospheric Administration (NOAA `www.ncdc.noaa.gov`) (Table 2.1). Limitations in data availability and type prevented using the same methodology to calculate each parameter. Lakes range in size from small ponds (less than $1 km^2$) to large lakes, such as Baikal, Titicaca, and the African Rift Valley Lakes (greater than 10000 km^2). Drainage basin sizes also vary widely, but larger lakes generally have large drainage basins. Precipitation and evaporation values also vary, ranging from less than 20 mm/year to several thousand mm/year. The variable with the greatest range of uncertainty is evaporation, as it is estimated using a wide variety of methods and with different timescales. Table 2.2 gives a listing of the lakes included in this study.

Table 2.1: Lake Data Sources, see text for definition of acronyms.

Continent	Data Source
Africa	*Ayenew* (2003); *Bergonzini* (2004); *Hamblin et al.* (2004) *Kutzbach* (1980); *Nicholson* (2002); *Song et al.* (2002)
Asia	*Morrill* (2004); *Qin and Huang* (1998), WLD, IWMI
Australia	*Bowler* (1981), IWMI, WLD
Europe	*George et al.* (2000); *Vassiljev* (1998) *Vassiljev et al.* (1995), IWMI, WLD
North America	*Allen* (2005); *Hostetler and Giorgi* (1995), NOAA, LTER, ELA, USGS NED files
South America	*Blodgett et al.* (1997); *Hastenrath* (1985), *Kessler* (1983), WLD

Many of the lakes included in the analyses have paleorecords or lake-level records that give an indication of the frequency of lake desiccation, which we use to estimate the desiccation interval. Using potential lake desiccation intervals provides another tool for evaluating the model, as the position of the lake relative to the line describing steady- state conditions should indicate its propensity to stabilize in each of the three different states. The majority of desiccation intervals were obtained from the literature or paleorecords (Table 2.1). Many North American lakes that formed after the last glacial were given a maximum desiccation interval of 10^3. Other lakes that we could not obtain data for were given the value of $\geq 10^3$, as this is an intermediate value.

2.3 Results

Figure 2.3 plots $A' - \Phi$ curves for different w-values and data for lakes from literature and on-line sources. The line to the left approximates highly vegetated forest conditions, or finer soil texture, while the right line approximates sparse to bare vegetation (*Wang et al.*, 2009). The steady-state condition for an individual lake is heavily dependent upon the basin vegetative cover, thus for individual lakes it may be important to consider a smaller, vegetation specific, envelope rather than the entire range between bare soil and forest lines.

In Figure 2.3, the majority of the lakes that have long desiccation intervals (permanent lakes) tend to plot either at $\Phi \leq 1$ or above the forest vegetation line. Lakes that have short desiccation intervals (ephemeral lakes) tend to plot below the bare soil curve. These lake data plotting positions are consistent with the steady-state conditions of the theory and the lake domains denoted in Figure 1a. However, some lakes deviate from these trends, which will be discussed below.

Prior knowledge of lake conditions in comparison to whether a lake plots in the permanent, vegetation sensitive, or ephemeral domain is useful in identifying possible controls on the hydrological conditions for a given lake. Based on the steady-state $A' - \Phi$ curves and lake plotting positions, we interpret that certain lakes are more sensitive to climatic perturbations than others. For example, a lake that plots significantly below the vegetation specific $A' - \Phi$ threshold line (or the region bounded by the forest and bare soil threshold lines) would require a larger increase in precipitation relative to evapotranspiration (i.e. decreases in Φ) to prevent the lake from desiccating.

The Australian saltpan lakes (Buchanan, Gaililee, Gardiner, and Frome) and American

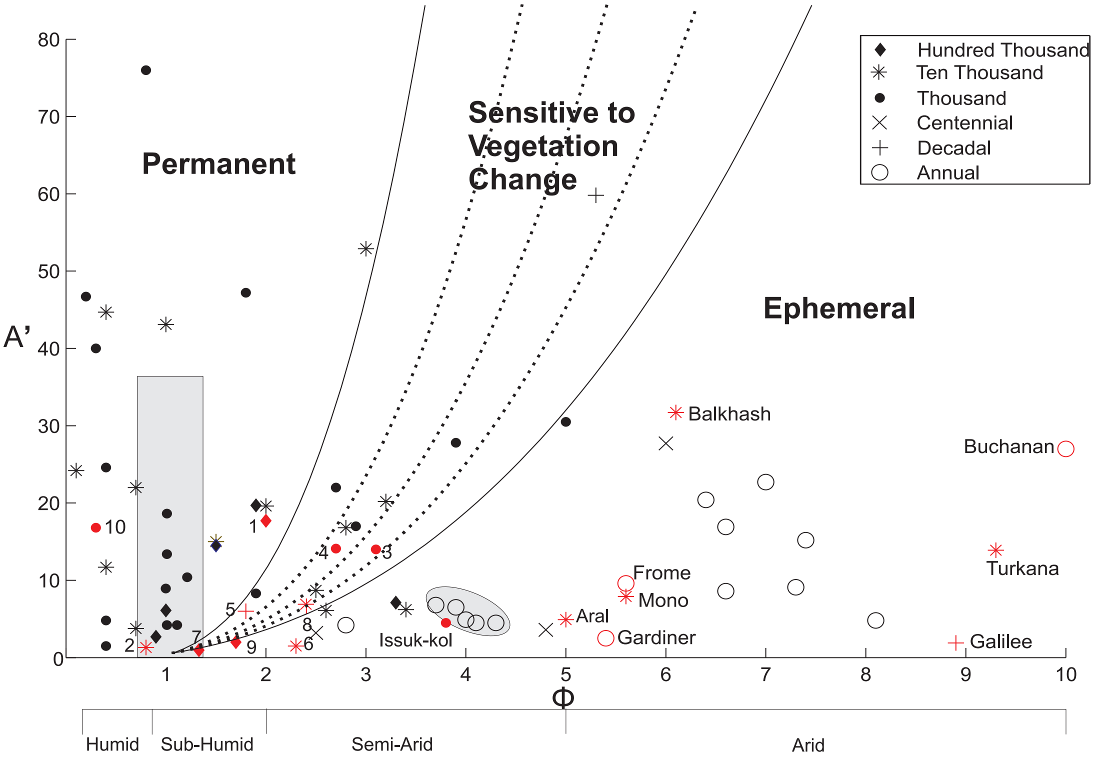

Figure 2.3: Lakes plotted on the $A' - \Phi$ domain along with (2.8) for a range of climates. The solid lines illustrate the effect of land cover for the two end-member vegetative possibilities, dense forest (*w*=2.5) and bare soil (*w*=.1). The dashed lines plot predicted A' as a function of Φ threshold values that result from different basin vegetative cover (*w*-values). The grey box represents the range of $A' - \Phi$ values for ELA and LTER lakes. The grey oval encompasses several southwestern US lakes. Lakes plotted in red are discussed in the paper. The number labels correspond to the following lakes: 1) Baikal, 2) Crater, 3) Crevice, 4) Foy, 5) George, 6) Keilambete, 7), Malawi, 8) Qinghai, 9) Titicaca, 10) Windermere. The lakes are grouped by potential desiccation time. Lakes that desiccate frequently tend to plot far below the $A' - \Phi$ thresholds, while lakes that never/rarely desiccate plot above of the threshold lines. Theoretically, lakes that plot within the envelope would be the most sensitive to land-use change.

Southwestern lakes would require a substantial change in climate to become permanent. Conversely, a lake that plots only slightly below the bare soil line would require only a small increase in precipitation to change from a basin that is losing water to a permanent lake. Thus, the saltpan lakes of Australia and ephemeral lakes of Southwestern America have a higher probability of desiccating than many other lakes, as shown in Figure 2.3, resulting from both the high PET and lack of a sufficiently large basin to compensate for evaporative losses. In the figure, lakes tend to group by desiccation interval (as indicated by the paleorecords), suggesting the large-scale importance of climate relative to local factors.

2.4 Discussion

In the $A' - \Phi$ domain presented in Figure 2.3, in agreement with the theory, the majority of the lakes with annual desiccation intervals plot within the ephemeral domain, while a significant number of the lakes that exhibit infrequent desiccation plot within the permanent region. However, several data points violate this observation. Some of the lakes that desiccate infrequently plot within the ephemeral domain, while some ephemeral lakes plot within the vegetation sensitive domain. According to the theory, lakes that plot within the threshold envelope (the upper and lower end member lines) are mainly dominated by surface water inflows and may be considered to be in steady-state with climate. The lakes that do not fall within this envelope (i.e. those that plotted outside the threshold envelope) are not in steady-state conditions and may be gaining or losing volume. Alternatively, these lakes may also be in steady state conditions due to other water fluxes, such as groundwater, that are not accounted for in the theory. We suggest that with the aid of the paleolimnologic records, the theory may be used to identify the dominant local hydrological controls of a lake.

Of the 171 lakes included within the study, lakes that plot within each category are, 125 permanent, 14 sensitive to change, 28 ephemeral, and 4 that plot at the boundary of the sensitive to change envelope. Lakes that most closely fit all of the model assumptions and plot within the sensitive to land use change envelope are Foy, Reservoir, Morrison, and Woods lakes. These lakes only require slight changes in basin vegetation (change in w less than 0.5) or changes in phi less than 1 to change the lake from plotting within steady-state conditions to either permanent or ephemeral. We do not have enough information for many of the other lakes that plot within the sensitive to change envelope to determine how well those lakes adhere to model assumptions. These four lakes also have highly resolved paleoreconstructions of lake level, suggesting that the model can help determine which lakes have the greatest potential for recording hydrologic variation within their sediments. The American southwestern lakes and Australian salt pan lakes all adhere to model assumptions, plot within the ephemeral realm of the plot, and desiccate frequently.

Outgoing fluxes are probably the most important hydrologic component not included within the model, but the model may help identify regions where this is a predominant control on the local hydrologic budget. Groundwater fluxes are indirectly included as basin runoff, but this is only accurate when the surface basin is the same size as the groundwater basin. Therefore, if a lake's groundwater basin is significantly larger than its surface water basin, the model may underestimate water coming into the lake. Groundwater estimates often require significant knowledge about the hydrologic budget of the lake, soil type, geology, etc. Crater Lake lies within the energy-limited portion of the permanent lakes domain, in other words it has greater water flux into the lake than loss by evaporation. Seepage may be a factor that maintains a climatological steady-state in this lake, thus preventing overflow (*Redmond*, 2007). Clearly in the Crater Lake case, the model explains why the lake maintains water levels although it loses significant volume to groundwater seepage. Conversely, Lake George, which plots within the vegetation-sensitive region, exhibits frequent, decadal, desiccation. Other lakes that plot within this domain rarely desiccate, suggesting that the lake has controls, other than A' or Φ, on local hydrology. Therefore, the decadal desiccation interval for Lake George may be a result of groundwater seepage (*Jacobson et al.*, 1991).

Surface water influxes and outflows, from rivers and streams, also alter the hydrologic balance. Streams that flow in and out of a lake have important influences on a lake's persistence despite climate and vegetation change. For example, Windermere, which plots within the permanent domain, has ouflowing streams. This outflow prevents the lake from continually increasing in volume, despite that the lake is located in the energy-limited domain and has $A' > 0$. Lake Turkana, on the other hand, is one of the world's largest permanent and alkaline desert lakes. The Omo River contributes $\sim 90\%$ of Lake Turkana's water and flows 621 miles from Ethiopia's Shewan Highlands to Kenya's Lake Turkana, across varying aridity conditions. The aridity index we use in the theory may not explain the climatic conditions throughout the basin, leading to a misclassification of the basin's hydrology. Lake Qinghai plots within the vegetation sensitive domain, yet stream and groundwater inputs do not compensate for losses, as Lake Qinghai decreased from $4980km^2$ to $4304km^2$ between 1908 to 1986 (*Qin and Huang*, 1998). Although the A' value increased during this time, the decrease in Lake Qinghai may largely be attributed to significant anthropogenic loss of riverine inputs, because many streams, such as the Buha River, are now dry (*Li et al.*, 2007).

Paleolimnologic records provide one method to explore whether the parameters used in the model adequately explain the steady-state conditions of a lake or region. Lake-level reconstructions allow for identification of lakes that show some sort of response to fluctuations within the hydrologic budget. Ideally, lakes that provide high-resolution records of lake-level fluctuations should plot near the threshold envelope, as these lakes require the smallest perturbations in PET or P to change whether the lake plots within the losing, gaining, or steady-state domains. This can be further refined for individual lakes if enough is known about the vegetation of the basin to constrain the w-values. Comparison of the model to paleolake records shows that most ”classic” sites used for lake-level reconstructions plot near the vegetation adjusted $A' - \Phi$ threshold line. Lakes, such as Lake Titicaca and Lake Malawi (African Rift Valley), plot almost on the threshold line, suggesting that these lakes are quite sensitive to climate fluctuations. Both of these lakes have highly resolved records that show large fluctuations in lake depth (*Baker et al.*, 2001; *Cohen et al.*, 2007; *Fritz et al.*, 2007). For large lakes, timescale is an important consideration in evaluating lake sensitivity to changes in the hydrologic balance; lakes may not be particularly sensitive to yearly fluctuations, but may provide high lake sensitivity on millennial timescales. Other lakes that plot within or near the threshold envelope, Lake Baikal, Lake Keilambete, and Foy Lake, also have highly resolved paleorecords that suggest these lakes are quite sensitive to disturbances in the hydrologic balance (*Bowler*, 1981; *Mackay*, 2007; *Stevens et al.*, 2006).

Some lakes that lie close to or within the threshold envelope do not provide sensitive P-E paleorecords. This means that although a lake should be sensitive to basin hydrologic variations, the lake may not provide a sensitive P-E record. Crevice Lake, Montana plots within the threshold envelope, but its paleorecords do not reflect changes in lake-level (*Bracht et al.*, 2008). Two potential characteristics may explain this observation. First, Crevice Lake lies next to the Yellowstone River, which buffers Crevice Lake from any significant lake-level changes (*Whitlock et al.*, 2008). Second, the basin is relatively steep sided, such that there is relatively little benthic habitat, for diatom growth, at any lake level. Thus, the fossil diatom record of past change is relatively insensitive to water-level change and the geomorphic setting buffers lake level.

The Wisconsin, USA LTER lakes plot within the permanent lake domain. These lakes have higher A' values than those predicted by the theory, which suggests that these lakes are either gaining water and thus continuously growing, or that they loose significant volume to groundwater seepage to maintain steady-state conditions. The groundwater system within this area is quite complex, and many of these lakes lose water to groundwater seepage (*Webster et al.*, 1996), which is consistent with our interpretation of the theory. The model suggests that these lakes would not provide highly detailed paleohydrologic records under the current climatic conditions.

From a more modern perspective, the model correctly identifies ephemeral lakes that are currently experiencing massive water losses, such as Lake Qinghai, Issuk-kol, Balkhash, Mono Lake, and the Aral Sea, which are rapidly shrinking as a result of negative water balances (*Aizen et al.*, 2007; *Micklin*, 2007; *Qin and Huang*, 1998). Although the theory does not include anthropogenic factors, it correctly identifies these lakes as ephemeral or with loosing trends under the current climate. Many of these lakes have significant anthropogenic influences that increase these already negative water-balance deficits. Some of these lakes desiccate infrequently, suggesting that either the massive water volumes slow complete desiccation, or that the lakes are able to maintain water levels with smaller A' than the model predicts.

The theory may be able to approximate the magnitude of climate change through the use of lake paleorecords. Paleolakes provide an opportunity to approximate climatic conditions during lake inception and desiccation. The model approximates steady-state conditions for lake size and basin size, under non-transient climate. However, through time, lakes often persist throughout a variety of climate regimes, which affect Φ and A'. For example, a lake that currently plots below its vegetation specific $A' - \Phi$ threshold line may have persisted through a wetter climate in the recent past. It may then be possible to estimate the climate (at least aridity index) at the time of lake formation. For example, it may be possible to estimate the aridity index during the Pleistocene inception of Lake Bonneville, not included in the plot due to lack of parameters (maximum surface area, 51,300 km^2), although the region is currently a salt flat (*Benson et al.*, 1992). We expect that, Lake Bonneville currently plots below any of the vegetation-specific threshold lines, but during lake inception, Φ would be considerably lower, allowing for the incoming fluxes to be greater than outgoing fluxes, and thus lake formation. This change in Φ would cause the lake to plot within the threshold envelope. This could provide a quantitative, rather than qualitative estimation of climatic change. Pollen records from surrounding regions could be used to estimate w at lake inception, to more accurately predict paleo-Φ values.

2.5 Conclusion

In this paper a lake water balance equation that predicts the basin to lake surface area ratio (A') for a given climate, characterized by an index of aridity (Φ, potential evaporation to precipitation ratio), and basin soil and vegetation conditions is developed, which is most appropriate for closed basin lakes in non-humid climates. Based on the theory a lake hydro-climatological classification idea is presented that stems from the work of Bowler (1981). Our classifications separates the $A' - \Phi$ domain to ephemeral, permanent and vegetation-sensitive lake regions. The model presented here is applied to multiple lakes to identify sites where surface area/basin area and PET/P are dominant controls on water level. Lakes that have strong alternative controls on lake level, such as the influences of groundwater, morphymetry, or those with significant outflow generally do not plot as the steady-state conditions would suggest. These parameters were not included in the model, because typically they are not known or easily estimated for most lakes.

The model suggests that a wide variety of lakes have some sensitivity to P-ET changes, as these lakes either plot within or near the threshold envelopes. Some of this sensitivity is based on the vegetation of the lake basin, which is incorporated in the model with the w-value. We used lakes around the globe to interpret their current status as well as potential factors that may cause deviation from model predictions in relation to their paleorecords. Interestingly, the theory has successfully identified the lakes that are known to be permanent and ephemeral in relation to their paleorecords that give desiccation intervals and lake level trends. Lakes that plot within the threshold envelope are most likely sensitive to land use change.

The model can be used both to estimate past aridity index values or to estimate which lakes are likely produce high-resolution P-PET paleorecords. Thus the model may be useful in planning paleoclimatic studies based on lacustrine records, as well as identifying modern lakes where climate has a large influence on surface water hydrology and lake level. As our theory identifies the impact of climate stress on lake hydrology, it may be used for both lake water management purposes, as well as examining the potential impacts of future climates on lake level trends.

Table 2.2: Lake location and parameters. Information for the exact location of each ELA lake was not available. SA is surface area and CA is catchment area. Lakes designated with an ⋆ are not included in the plot.

Lake	Latitude	Longitude	SA (km2)	CA (km2)	Precip (mm)	Evap (mm)
Africa						
Abiyata	7°30’N	38°30’E	203	10740	552	1653
Malawi	13°30’S	34°00’E	6400	6593	1350	1700
Massoko	9°20’S	33°45’E	0.4	0.5	1300	500
Rukwa	8°00’S	32°25’E	4000	78200	995	2000
Tanganyika	10°00’ S	30°00’ E	32600	197400	1302	1251
Victoria	1°25’S	33°10’E	68800	184000	1780	1591
Langano	7°37’N	38°42’E	230	2000	770	1921
Modern *Chad*⋆	13°00’N	14°00’E	25000	2500000	500	1297
Paleolake Chad	13°0’N	14°0’E	350000	2500000	391	1297
Shala	7°28’N	38°31’E	370	2300	627	2110
Turkana	3°03’N	36°01’E	6750	130860	250	2335
Ziway	8°00’N	38°49’E	440	7380	734	2022
Asia						
Ahung Co	31°20’N	92°5’E	3.6	100	430	760
Aral	45°00’ N	60°00’ E	66500	1006460	200	1317
Baikal	53°30’N	108°10’E	31500	557000	677	1321
Balkhash	46°32’N	74°52’E	16434	521000	187	1141
Ba Be	22°02’N	105°04’E	4.5	454	1445	1354
Dal	34°02’N	75°04’E	21	316	655	957
Dong-hu	30°03’N	114°02’E	28	97	1450	1037
Issuk-kul	42°30’N	77°30’E	6236	28127	258	984
Phewa	28°01’N	83°05’E	5	110	1556	1151
Qinghai	37°00’ N	100°00’ E	4304	29691	378	1459
Australia						
Buchanan	21°38S	145°52’E	115	3110	227	3000
Eyre	28°30’S	137°20’E	9790	1316000	500	1297
Frome	30°37’S	139°52’E	2550	24500	232	1300
Gaililee	22°19’S	145°50’E	260	500	360	3000
Gairdner	34°57’ S	118°08’E	4520	11180	350	1900
George	35°4’S	149°25’E	150	906	600	1050
Gregory	25°38’S	119°58’E	387	33160	300	1669
Keilambete	38°12’S	142°52’E	2.7	4.1	400	900
Torrens	31°02’S	137°51’E	5640	27000	186	1500
Tyrrell	35°21’S	142°50’E	155	647	323	890
Woods	17°43’S	139°30’E	423	25300	302	1600

Lake	**Latitude**	**Longitude**	**SA (km2)**	**CA (km2)**	**Precip (mm)**	**Evap (mm)**
Europe						
Amara	45°13’N	27°17’E	1.5	47	429	836
Balta Alba	45°02’N	27°02’E	11.0	91.6	429	836
Banyoles	42°08’N	2°45’E	1.1	11.4	804	937
Bassenthwaithe	54°39’N	3°13’W	5.3	237	1300	500
Blelham Tarn	54°24’N	2°59’ W	0.1	4	1918	500
Chervonoje	52°2’N	27°5’E	40.0	353	656	663
Esthwaite Water	54°21’N	2°58’W	1.0	17	1912	500
Grasmere	49°04’N	1°15’W	0.6	28	2553	500
Karujarv	58°23’N	22°13’E	3.3	16.1	238	235
Kir jaku*	59°15’N	27°35’E	0.2	30.8	238	235
Lake Bysjon	55°40’N	13°32’E	0.2	0.9	587	619
Loch Shiel	56°05’N	5°04’W	20.0	234	1300	500
Vijandi	58°20’N	25°35’E	1.6	66.8	238	235
Windermere (NB)	54°21’N	2°56’W	8.1	198	1300	500
Windermere (SB)	54°21’N	2°56’W	6.7	32	1300	500
North America						
Crater	42°56’N	122°06’W	53.2	67.8	1692	1270
Crevice	47°52’N	113°39’W	0.1	0.2	*356*	*1100*
Foy	48°5’N	114°15’W	0.9	13.6	406	1100
Great Salt	40°42’N	112°23’W	4400	89000	419	1349
Mono	38°0’N	119°0’W	227	1800	355	1981
Morrison	44°36’N	113°02’W	0.1	2	406	1100
Pyramid	40° N	119°30’W	430	2620	500	1300
Reservoir	45°07’N	113°27’W	0.2	2.8	381	1100
Sammamish	47°33’N	122°03’W	19.8	255	800	818
Washington	47°37’N	122°15’W	87.6	1274	799	1234
Yellowstone	44°30’N	115°30’W	360	7100	516	973
Southwest						
Animas	32°28’N	108°54’W	374	5670	250	1840
Cloverdale	31°00’ N	108°00’ W	102	460	410	1780
Encino	34°00’ N	105°00’ W	96	620	350	1370
Estancia	34°45’N	106°03’W	1125	5050	310	1270
Goodsight	32°19’N	108°45’W	65	590	250	1830
Otero	32°32’N	105°46’W	745	126000	250	1660
Pinos Well	34°27’N	105°38’W	82	560	360	1320
Playas	31°50’N	108°34’W	49	1120	270	1900
Sacramento	32°45’N	105°46’W	86	780	250	1650
San Agustin	33°52’N	108°15’W	786	3880	290	1150
Trinity	33°40’N	106°28’W	207	4240	250	1590

Lake	Latitude	Longitude	SA (km2)	CA (km2)	Precip (mm)	Evap (mm)
LTER						
Allequash	46°02’N	89°37’W	1.7	6.3	800	1000
Arrowhead	45°54’N	89°41’W	0.4	2.4	800	1000
Beaver	46°12’N	89°35’W	0.3	4.6	800	1000
Big	46°09’N	89°46’W	3.3	10.4	800	1000
Big Crooked	46°02’N	89°51’W	2.7	6.0	800	1000
Big Gibson	46°08’N	89°33’W	0.5	1.1	800	1000
Big Muskellunge	46°01’N	89°36’W	3.6	7.8	800	1000
Boulder	45°08’N	88°38’W	2.2	14.3	800	1000
Brandy	45°54’N	89°42’W	0.4	1.0	800	1000
Crampton	46°12’N	89°28’W	0.3	0.7	800	1000
Crystal	46°00’N	89°36’W	0.4	1.8	800	1000
Diamond	46°02’N	89°42’W	0.5	1.2	800	1000
Flora	46°10’N	89°39’W	0.4	2.2	800	1000
Heart	46°05’N	89°16’W	0.1	0.5	800	1000
Ike Walton	46°02’N	89°48’W	5.7	13.2	800	1000
Island	46°06’N	89°47’W	3.6	12.5	800	1000
Johnson	46°08’N	89°31’W	0.3	1.7	800	1000
Katherine	45°48’N	89°42’W	2.1	6.6	800	1000
Kathleen	45°14’N	88°38’W	0.1	0.3	800	1000
Katinka	46°12’N	89°47’W	0.7	1.6	800	1000
Lehto	46°01’N	90°02’W	0.3	7.4	800	1000
Little Crooked	46°08’N	89°41’W	0.6	3.2	800	1000
Little Spider	45°58’N	89°42’W	0.9	2.1	800	1000
Little Sugarbush	46°01’N	89°51’W	0.2	0.8	800	1000
Little Trout	46°04’N	89°51’W	4.1	7.6	800	1000
Lower Kaubeshine	45°48’N	89°44’W	0.8	2.8	800	1000
Lynx	45°56’N	89°13’W	1.2	2.8	800	1000
McCullough	46°11’N	89°34’W	0.9	3.3	800	1000
Mid	45°51’N	89°39’W	1.0	2.7	800	1000
Minocqua	45°52’N	89°41’W	8.1	11.7	800	1000
Muskesin	46°01’N	89°54’W	0.5	1.3	800	1000
Nixon	46°05’N	89°33’W	0.5	9.6	800	1000
Partridge	46°04’N	89°30’W	1.0	3.3	800	1000
Randall	46°01’N	90°01’W	0.5	4.3	800	1000
Round	46°10’N	89°42’W	0.7	5.7	800	1000
Sanford	46°10’N	89°41’W	0.4	1.5	800	1000
Sparkling	46°00’N	89°41’W	0.6	1.1	800	1000
Statenaker	45°58’N	89°46’W	0.8	1.9	800	1000
Stearns	45°59’N	89°48’W	1.0	2.0	800	1000
Tomahawk	45°49’N	89°39’W	15.0	25.4	800	1000

Lake	**Latitude**	**Longitude**	**SA (km2)**	**CA (km2)**	**Precip (mm)**	**Evap (mm)**
Trout	46°02’N	89°40’W	15.7	23.6	800	1000
Upper Kaubeshine	45°47’N	89°44’W	0.7	2.1	800	1000
White Birch	45°39’N	91°09’W	0.5	1.0	800	1000
White Sand	46°05’N	89°35’W	3.0	5.5	800	1000
WildRice⋆	46°03’N	89°47’W	1.5	153.1	800	1000
Wildcat	46°10’N	89°37’W	1.4	4.1	800	1000
ELA Lakes						
93	49°40’N	93°43’W	5.5	60	684	525
106	49°40’N	93°43’W	3.7	121	684	525
109	49°40’N	93°43’W	14.9	42	684	525
110	49°40’N	93°43’W	5.3	34	684	525
111	49°40’N	93°43’W	9.6	339	684	525
114	49°40’N	93°43’W	12.1	58	684	525
115	49°40’N	93°43’W	6.5	119	684	525
149	49°40’N	93°43’W	26.9	94	684	525
164⋆	49°40’N	93°43’W	20.3	4984	684	525
165⋆	49°40’N	93°43’W	18.4	4802	684	525
191	49°40’N	93°43’W	19.4	338	684	525
220	49°40’N	93°43’W	1.6	20	684	525
221	49°40’N	93°43’W	9	82	684	525
222	49°40’N	93°43’W	16.4	204	684	525
223	49°40’N	93°43’W	27.3	260	684	525
224	49°40’N	93°43’W	25.9	98	684	525
225	49°40’N	93°43’W	4	31	684	525
226	49°40’N	93°43’W	16.1	97	684	525
227	49°40’N	93°43’W	5	34	684	525
239	49°40’N	93°43’W	56.1	391	684	525
240	49°40’N	93°43’W	44.1	720	684	525
260	49°40’N	93°43’W	34	166	684	525
261	49°40’N	93°43’W	5.6	42	684	525
262	49°40’N	93°43’W	84.2	1230	684	525
265	49°40’N	93°43’W	13.1	71	684	525
302	49°40’N	93°43’W	23.7	103	684	525
303	49°40’N	93°43’W	9.5	54	684	525
304	49°40’N	93°43’W	3.4	26	684	525
305	49°40’N	93°43’W	52	237	684	525

Lake	**Latitude**	**Longitude**	**SA (km2)**	**CA (km2)**	**Precip (mm)**	**Evap (mm)**
309⋆	49°40’N	93°43’W	2.6	560	684	525
310	49°40’N	93°43’W	49.7	539	684	525
373	49°40’N	93°43’W	27.6	83	684	525
375	49°40’N	93°43’W	18.9	231	684	525
377	49°40’N	93°43’W	26.7	2030	684	525
378	49°40’N	93°43’W	24.3	136	684	525
382	49°40’N	93°43’W	36.9	205	684	525
383	49°40’N	93°43’W	5.6	40	684	525
385	49°40’N	93°43’W	24.9	102	684	525
421	49°40’N	93°43’W	17	51	684	525
428	49°40’N	93°43’W	6	44	684	525
442	49°40’N	93°43’W	15.2	184	684	525
470	49°40’N	93°43’W	5.7	168	684	525
622	49°40’N	93°43’W	38.6	419	684	525
623	49°40’N	93°43’W	36	651	684	525
624	49°40’N	93°43’W	2	753	684	525
626⋆	49°40’N	93°43’W	27.9	388	684	525
629	49°40’N	93°43’W	35.5	348	684	525
658	49°40’N	93°43’W	63.1	125	684	525
South America						
Amatitlan	14°08’N	90°06’W	15.2	368	1124	1150
Chapala	20°01’N	103°06’W	1112	52500	893	1601
Laguna de Rocha	34°04’S	54°01’W	72	1312	1073	1058
Paleo Tauca 1	13°28’S	72°02’W	22700	73500	600	1494
Poopo	18°33’S	67°05’W	1000	27700	250	1494
Paleo Tauca 2	13°28’S	72°02’W	20300	73500	310	1494
Titicaca	15°50’S	69°20’W	285006	580000	737	1270

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Chapter 3

Synchronous late-Holocene climatic change inferred from four western Montana lakes

Abstract

Late-Holocene environmental and climatic conditions were reconstructed from diatoms and associated geochemical data for four western Montana lakes: Crevice Lake, Foy Lake, Morrison Lake, and Reservoir Lake. Foy and Reservoir Lakes provide highly resolved records of the hydrologic balance, while the records of Crevice and Morrison Lakes primarily record temperature impact on lake thermal structure. The lakes show synchroneity in timing of shifts in diatom community structure, but the nature of these changes differ amongst the lakes. All four lakes show significant changes in four discrete intervals: 2200-2100, 1700-1600, 1350-1200, and 800-600 cal yr BP. Similarities in the timing of changes among the lake basins suggest overlying regional climatic controls on the lake systems. The 800-600 cal yr BP shift is seen in other paleorecords throughout the Great Plains and western US, associated with the transition from the Medieval Climate Anomaly to the Little Ice Age. These changes in diatom dominance are correlated to environmental perturbations and hence climatic variability. Large-scale climatic mechanisms that influence these lake environments most likely result from interactions between Pacific and Atlantic sea-surface temperatures, which are then locally modified by topography.

3.1 Introduction

The importance of the northern Rocky Mountains in the hydrologic system of western America has led to many recent studies to quantify the nature and timing of past precipitation and droughts (Cook et al., 2007; Gray et al., 2007; Büntgen et al., 2005; Stone and Fritz, 2006). It is difficult to capture regional patterns of past climatic variability in this area, because mountains modify large-scale atmospheric circulation via various mechanisms (Williams et al., 1996). These mechanisms include channelization of winds, rainshadow effects, and glacial interactions (Barry, 1990). As a result, sites separated by only a few miles may experience significantly different local climate, including differences in both temperature and precipitation (Barry, 1992). The spatial heterogeneity of climate in montane regions raises doubt about the accuracy or usefulness of single site paleorecords in portraying a coherent representation of regional climate.

At present, relatively few high-resolution paleoclimatic records that span the past 2500 years are available for the northern Rocky Mountain region. Thus, the degree of spatial heterogeneity of past climate within the region is not yet defined. Tree-ring records are relatively abundant, but the shorter time scales, which span only the last several hundred years to the last millennium, may not capture the full range of regional climatic variability that is characteristic at multi-decadal to centennial scales (Gray et al., 2004; Briffa et al., 2001; Salzer and Kipfmueller, 2005).

Here we reconstruct and compare patterns of environmental variation at four western Montana lakes: Crevice Lake, Foy Lake, Morrison Lake, and Reservoir Lake. The lakes are all located within a similar climatic and geographic setting. Diatoms are used as the primary proxy for reconstructing past limnological and climatic history. We apply several different statistical methods to the diatom stratigraphies to determine if the nature and timing of changes in the diatom community structure are similar amongst the lakes and therefore to evaluate whether or not the variation is likely a direct response to regional environmental forcings related to climate.

3.1.1 Environmental Setting

All four lakes are located within the northern Rocky Mountains of western Montana (Figure 3.1). Crevice Lake is located within Yellowstone National Park, Foy Lake is in the Salish Mountains, and both Reservoir and Morrison Lakes are within the Beaverhead

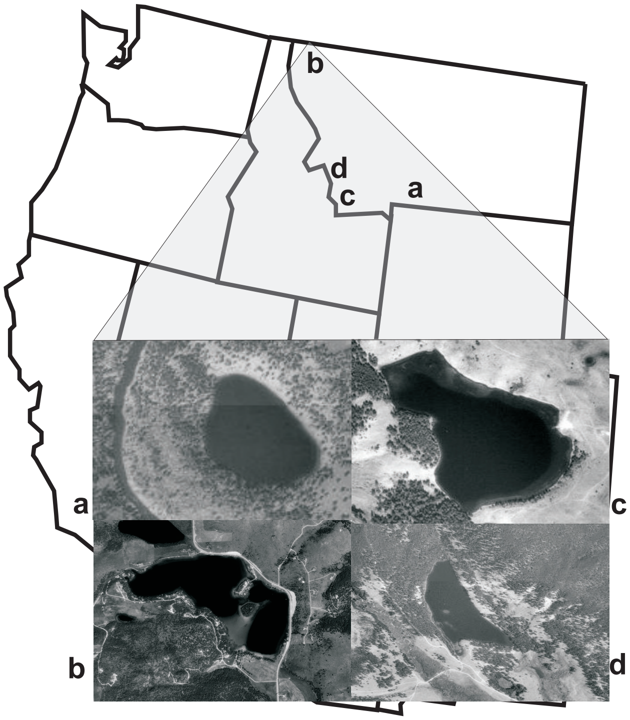

Figure 3.1: The location of the four lakes included in this study, Crevice Lake (a), Foy Lake (b), Morrison Lake (c), and Reservoir Lake (d).

Mountains. The lakes are all sub-alpine and mesotrophic to eutrophic (Table 3.1). The Crevice Lake basin is dominated by mixed conifer and sagebrush vegetation. Common species include *Pseudotsuga menziesii*, *Junipenus scopulorum*, *Pinus flexilis*, and *Artemisia tridentata*. Around the lake, *Betula occidentalis*, *Alnus incana*, and*Salix* are common, with *Carex*, *Scirpus*, and *Typha latifolia* around the lake margin. Vegetation within the Foy Lake basin includes *P. menziesii*, *Pinus ponderosa*, *Larix occidentalis*, *Juniperus scopulorum*, and *Pinus contorta* (Power et al., 2006). Morrison Lake is surrounded by *P. contorta*. The Reservoir Lake basin contains open pine forest that includes *P. menziesii*, *P. contorta*, *Artemisia tridentata*, and *Poaceae* (Gage, 2008). The southern edge of the lake contains abundant *Nuphar* and *Scirpus*.

Crevice, Reservoir, and Morrison Lakes are small, remote, closed-basin lakes. Foy Lake is the largest of the four lakes (Table 3.1), with significant human development surrounding the lake and an intermittent outlet. All the lakes likely result from glacial activity that carved out deep depressions, and all the lakes are situated in glacial till. Each of

Table 3.1: Limnologic and geographic characteristics of each lake. TP (mg/L) is total phosphorus, TN (mg/L) is total nitrogen, Conduc is conductivity, and SA stands for surface area.

Lake	Lat.	Long.	SA (km^2)	TP	TN	Secchi (m)	pH	Conduc. (μS)
Crevice	$45°0'$N	$110°36'W$	0.1	.03	.47	7.0	8.5	600
Foy	$48°10'$N	$114°21'W$	0.9	-	-	7.0	7.5	1090
Morrison	$44°36'$N	$113°2'W$	0.1	.02	.75	7.0	8.8	220.0
Reservoir	$45°7'$N	$113°27'W$	0.2	.04	.41	7.0	8.3	20.0

the lakes is at least 15 m deep (Figure 3.2). The water depth in all lakes is conducive to seasonal or yearly anoxia, which aids in preservation of sedimentary structures and laminations. Crevice and Foy lakes contain annually laminated sediments (varves), which are organic-carbonate couplets. All the available limnological data are summarized in Table 3.1.

3.1.2 Climatic Setting

Western Montana has an alpine-continental climate (Mock, 1996). In most regions, the majority of precipitation falls during the winter and spring seasons, with considerably drier summer and fall seasons. Crevice Lake is located within Montana climate division 5, Foy Lake within climate division 1, and both Morrison Lake and Reservoir Lake are within climate division 2 (`www.esrl.noaa.gov/psd/data/usclimdivs/data/map.html`). Two climate monitoring stations are located within 8 km of Crevice Lake: Mammoth Hot Springs, WY (1901 m) and Gardiner, MT (1619 m). The two sites vary considerably in precipitation, receiving 393.7 mm/yr and 236.9 mm/yr, respectively, reflecting the elevational differences (`www.ncdc.noaa.gov`). The vegetation surrounding Crevice Lake, in comparison with Mammoth Hot Springs and Gardiner, suggests that the Crevice Lake may not receive the same amount or timing of precipitation events as either of the long-term

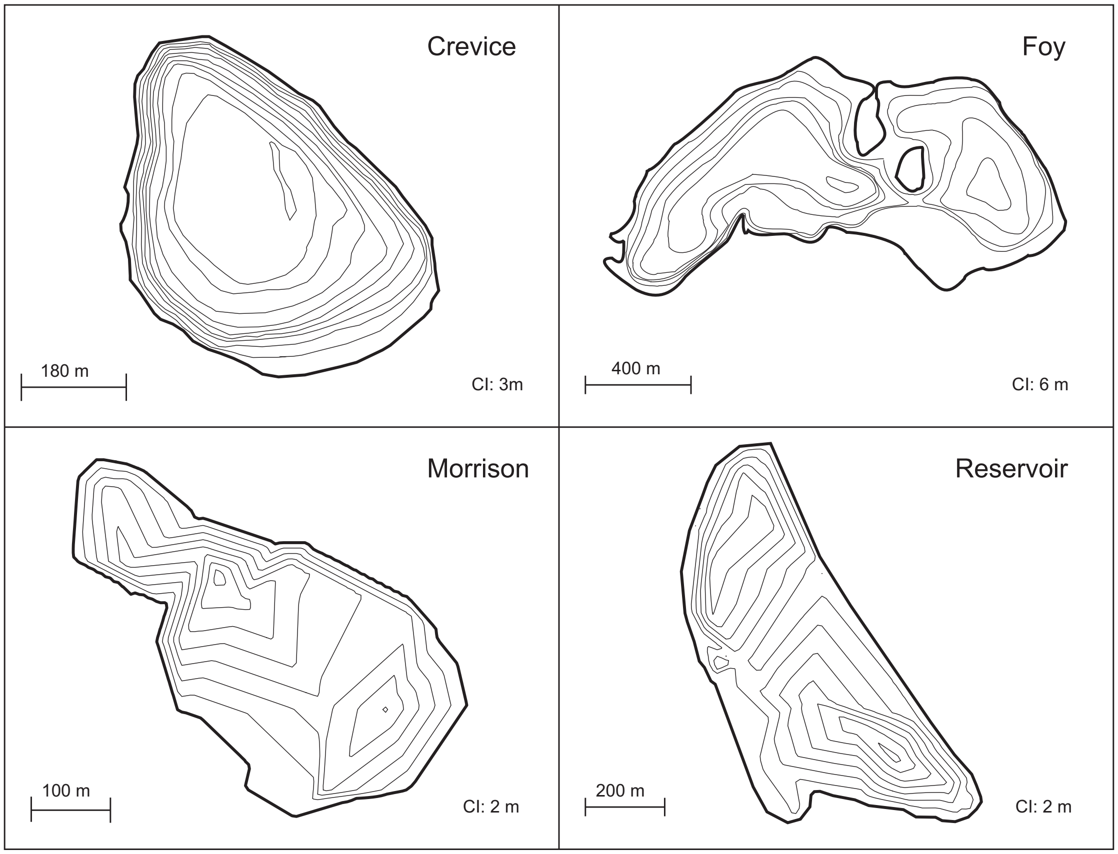

Figure 3.2: Bathymetric maps of the four lakes. Cores were taken from the deepest portion of each lake. The Crevice Lake bathymetric map is from the Yellowstone National Park Service, the Foy Lake map is from Stone and Fritz (2004). The Morrison Lake and Reservoir Lake maps are from measurements made during the 2007 field season, which were then gridded using Surfer. CI refers to the contour interval used in delimiting bathymetry.

climate monitoring stations.

Climatological data from Kalispell, Montana (`www.ncdc.noaa.gov`), located 4.8 km from Foy Lake, suggest that the lake receives the majority of its precipitation during May and June, while the rest of the climate division receives the majority of its precipitation during October-March. Weather station data from Kalispell report an average precipitation of 381 mm/yr and an average annual temperature of 6.1°C. The fact that Foy Lake and Kalispell differ in the timing of major precipitation events relative to the rest of climate division 1 demonstrates the high degree of spatial heterogeneity of regional climate. Morrison and Reservoir Lake are extremely remote, without local meteorological stations to provide weather data to infer local climatological trends. It is assumed, based on regional patterns, that these two lakes receive the majority of their precipitation between October and March. Western Montana climate is heavily influenced by the strength and position of the North American polar jet stream (Whitlock and Bartlein, 1993). The northern portion of Yellowstone National Park (YNP), where Crevice Lake is located, receives significant precipitation during summer that originates in the Gulf of Mexico. The other sites are dominated by winter precipitation originating from the Pacific (Whitlock and Bartlein, 1993).

3.2 Methods

3.2.1 Coring

Multiple cores were recovered from the ice surfaces of Crevice, Reservoir, Morrison, and Foy lakes, using freeze cores to retrieve the surface mud (except for Morrison) combined with either Austrian or Livingston cores taken from the ice surface for the underlying sediments. Crevice lake was cored during February 2001, Foy Lake in the winters of 2000 and 2002, Reservoir Lake during 1996, and Morrison Lake during 2000. The freeze and piston cores were combined for a contiguous sequence based upon overlapping sedimentological features. The cores for Crevice Lake and Foy Lake contain varves, which are organic-carbonate couplets that are useful in age model devolpment. Lake cores were subsampled at 2-4 mm intervals for Crevice Lake, 1-cm intervals for Reservoir Lake, 0.5 cm intervals for Morrison Lake, and by annual varves for Foy Lake. Each sample was homogenized before sub-sampling for various biological and geochemical proxies.

3.2.2 Diatoms & Geochemistry

Contiguous samples for diatom and geochemical analyses were taken for all lakes. Diatom subsamples were treated with cold hydrochloric acid and hydrogen peroxide to digest the carbonate and organic material, respectively. Rinsed samples were dried onto coverslips and mounted onto slides with permanent mounting medium (Battarbee and Kneen, 1982). A minimum of 300 diatom valves was counted per slide, with the exception of Morrison Lake. The extreme dissolution of some portions of the Morrison Lake core prevented a count of 300 diatom valves for many samples.

Total inorganic carbon (TIC) and carbon to nitrogen ratios (C:N) were measured on freeze-dried and ground samples. The C:N ratios were calculated from the total carbon and total nitrogen values. A Costech Analytical ECS 4010 measured carbon and nitrogen content via dry combustion analysis. Hydrogen peroxide was added to ground samples to remove organic carbon prior to TIC coulometric titration. TIC analysis was performed by a CM 5012 UIC coulometer.

3.2.3 Age Models

The development and robustness of the four age models differ amongst lakes, because of the availability of counted varves or dateable material. The Crevice Lake age model was developed using both AMS ^{14}C dates and varves (Whitlock et al., 2008). A third order polynomial was used for the age model (Figure 3.3a). The Foy Lake chronology (Stevens et al., 2006) was developed using varve counts and AMS ^{14}C dates. A polynomial was fitted to varve and radiocarbon dates to generate the chronology (Figure 3.3b). Morrison Lake has two ^{14}C dates to constrain the age model (Figure 3.3c). Core chronology for Reservoir Lake uses both ^{210}Pb dating of the freeze core and ^{14}C dating of charcoal and macrofossils in the long core (Figure 3.3d). One of Reservoir Lake's ^{14}C dates was not used in the age model as it was thought to contain reworked material (Gage, 2008). All radiocarbon dates were calibrated to calendar years using Calib 5.2 (Stuvier et al., 1993). Table 3.2 shows the materials and associated ages used to develop the core chronology for each lake.

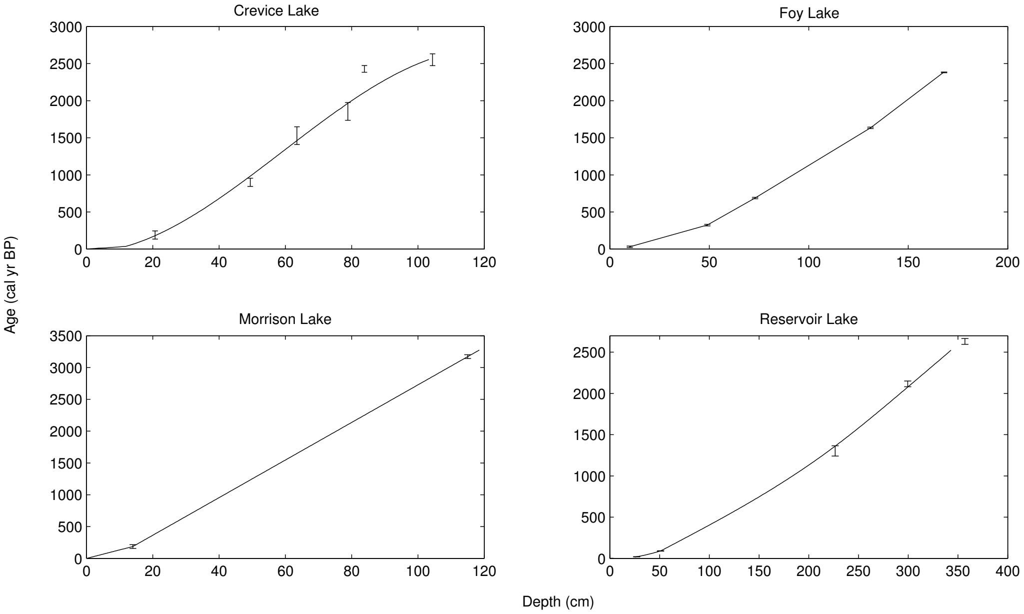

Figure 3.3: Age models for the four lakes. The Crevice Lake age model uses ^{14}C dates and varves. The Foy Lake age model contains ^{14}C, ^{210}Pb, and varves. The Reservoir Lake age model uses ^{14}C and ^{210}Pb dates. The Morrison Lake age model only uses three dates, the top of the core as 0 cal yr BP and two ^{14}C dates. See text for further details.

3.2.4 Statistical Techniques

Multiple statistical techniques were employed to evaluate the coherence in timing and direction of change among the four lake core records. First, we plotted the species percent abundances through time to describe significant changes in diatom community structure. A zonation scheme was then developed for each lake with constrained cluster analysis (CONISS) on square root transformed data, using Psimpoll 4.10 (Bennett, 1996). In addi-

Table 3.2: Samples used for development of the age models for Crevice, Morrison, and Reservoir Lakes. The Foy Lake age model is described in (Stevens et al., 2006). Sample denoted with an ^{a} were excluded in the age model reconstructions, while ^{b} is the sediment-water interface and ^{c} are ^{210}Pb dates. Median ages are in yr BP.

Lake	Sample	Material	Depth (cm)	^{14}C Age	Cal. 2σ	Med. Age
Crevice	CV-25	Needle	20.45	210	59-320	190
Crevice	CV-108/109	Needle	49.45	1010	791-1010	900
Crevice	CV-148	Needle	63.3	1610	1298-1741	1529
Crevice	CV-184	Needle	75.85	1920	1562-2149	1855
Crevice	CV-213a^a	Bark	83.85	2390	2337-2519	2428
Crevice	CV-272	Needle	104.15	2500	2362-2742	2552
Morrison	MOR-14	Twig	14	170	142-218	187
Morrison	MOR-115	Wood	115	2980	3101-3240	3171
Reservoir^b	RES-0	-	0	-	-	0
Reservoir^c	RES-27	-	0	-	-	20
Reservoir^c	RES-51	-	0	-	-	90
Reservoir	RES-1757	Needle	1751	1340	1179-1310	1275
Reservoir	RES-1830	Needle/Charcoal	1830	2095	1952-2152	2067
Reservoir	RES-1888	Needle	1888	2545	2496-2748	2631

tion to visual comparisons of zonation schemes, detrended correspondence analysis (DCA) and spectral analysis were performed on the diatom data to determine similarities in patterns of change among datasets. Each DCA was run on both the entire species dataset and a dataset containing only the species that achieved at least 5% abundance. Canoco 4.5 was used to perform the DCA analyses (ter Braak and Smilauer, 2002). The DCA component loadings were then re-sampled using AnalySeries to obtain the constant sampling interval necessary for spectral analysis (Paillard et al., 1996). The re-sampled datasets were then run with the SSA-MTM Toolkit multi-taper method for spectral analysis (Ghil et al., 2002).

3.3 Results

3.3.1 Lithology & Geochemistry

The Crevice Lake core consists of light-brown laminated gyttja with some sulfur nodules. Fine couplets, approximately 0.3 mm thick, are likely varves based upon comparison with ^{14}C ages (Whitlock et al., 2008). Foy Lake, during the interval considered, consists of finely laminated red and green gyttja, with a highly carbonaceous zone (18-31 cm) (Stevens et al., 2006). The fine organic/carbonate couplets are interpreted as varves. The Morrison and Reservoir Lake cores both consist of laminated (non-varved) light brown gyttja. Total inorganic carbon (TIC) data are available for Reservoir Lake, which range from non-detectable levels to 1500 ppm. Carbon to nitrogen (C:N) values range from 1-40 for Foy Lake and 0-15 for Reservoir Lake.

3.3.2 DCA Results

Diatom stratigraphy and the dominant diatom zones of each lake are plotted in Figures 3.6 to 3.9. Ordination analysis provides a method to summarize the variability within the diatom species data. The lakes have large gradients of change in diatom species composition in multi-dimensional space and do not exhibit a linear response; therefore, detrended correspondance analysis (DCA) is the preferred ordination technique (ter Braak and Smilauer, 2002). Figure 3.4 shows the DCA results for all four lakes. The first axis is plotted for Crevice, Foy, and Reservoir Lakes, while the third axis is plotted for Morrison Lake. For Crevice Lake, DCA1 is almost an exact replica of the *C. bodanica* curve (Figure 3.6). The Foy Lake DCA1 corresponds to the sum of the benthic species (Figure 3.7). DCA3 for Morrison Lake correlates to dissolution (diatom to microspheres ratio) (Figure 3.8). The Reservoir Lake DCA1 seems to correspond to the *C. stelligera* curve for that lake (Figure

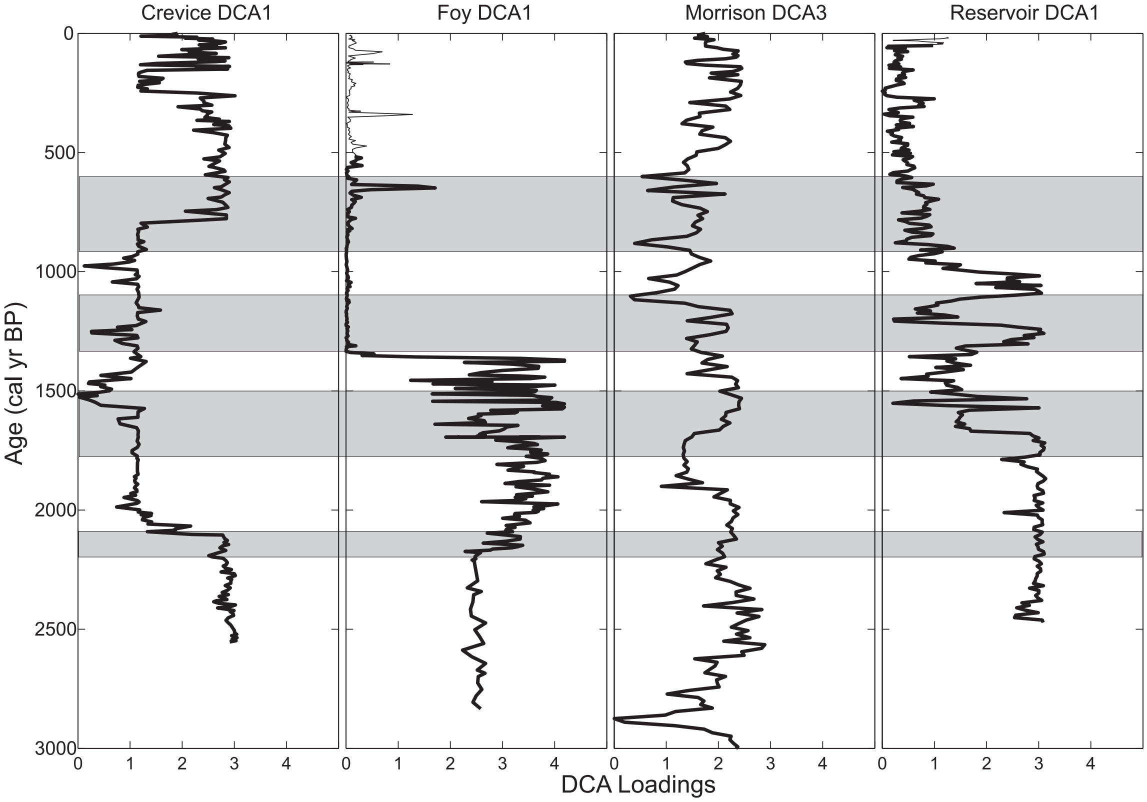

Figure 3.4: Canoco DCA results. The first axis is plotted for Crevice Lake, Foy Lake, and Reservoir Lake, while the third axis is plotted for Morrison Lake. The grey bands represent periods that all four lakes show significant changes within the diatom record.

3.9). These are the axes used for spectral analysis. The DCA's show patterns similar to the zonation schemes described below.

3.3.3 Spectral Analysis Results

The MTM spectral analysis shows several dominant periodicities for each lake (Figure 3.5). Each subplot contains 3 lines, the spectral frequency, 95%, and 99% confidence lines. Only peaks above the 99% confidence line are considered significant in this analysis. Crevice Lake shows dominant periodicities from 34-37 years and 52-58 years. The dominant frequencies for Foy Lake are 32-36, 43, and 58-62 years. Dominant periodicities for

Morrison Lake are 54-58 and 74-78 years. Significant peaks also are present at 98, 102, 138, and 151 years. Reservoir Lake periodicities are 37-42, 54-56, 81, and 250 years.

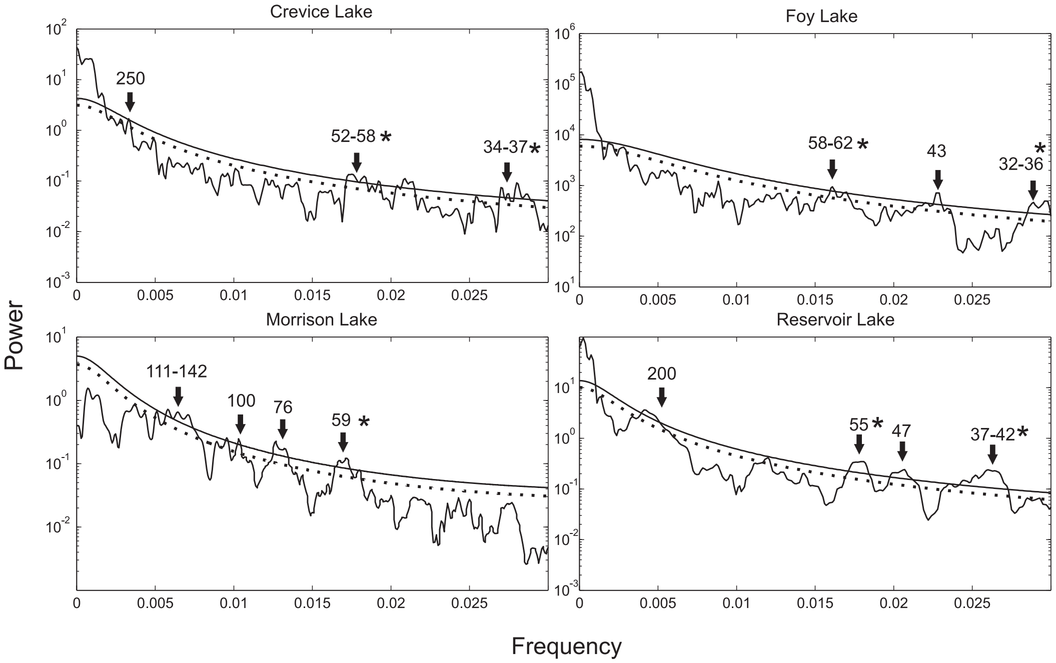

Figure 3.5: Spectral analysis results for each of the four lakes. The solid line is the 99% confidence level, while the dotted line is the 95% confidence level. Crevice Lake, Foy Lake, and Reservoir Lake show periodicities consistent with the PDO and AMO, while Morrison Lake only shows periodicities consistent with the PDO. The ⋆ denotes frequencies consistent with either the PDO or AMO.

3.4 Discussion

3.4.1 Limnological History

A comparison of the diatom stratigraphies of the four lakes suggests that the lake show some common intervals of change that likely reflect climate forcing, but the mechanisms of climatic impact vary somewhat among the lakes. Crevice Lake exhibits four main units based on differences in diatom community structure (Figure 3.6). From 2550-2100 cal yr BP, the lake is dominated by two planktonic species, *Stephanodiscus minutulus*, a high phosphorus (P) specialist, and *Synedra tenera* (a low P specialist). Neither species does well under low N conditions. *S. minutulus* blooms during times of prolonged spring mixing, when P is mixed throughout the water column, and *S. tenera* is efficient under low-phosphorus conditions (Bracht et al., 2008). In the Yellowstone region lakes, *S. tenera* increases in relative abundance after *S. minutulus* blooms, but prior to the onset of stratification. Thus, the co-dominance of these species, in the sediments, may be indicative of years of particularly long periods of isothermal mixing (Bradbury, 1988; Morabito et al., 2001; Interlandi et al., 1999). From 2100-800 cal yr BP the diatom assemblage shifts to a *Cyclotella*-dominated community. The two dominant taxa, *Cyclotella bodanica* and *Cyclotella michiganiana*, are summer taxa that thrive under low nitrogen levels and in well stratified water columns (Interlandi et al., 1999). The presence of these two species suggests long warm summers that intensify lake stratification. The period from 800 cal yr BP to present is dominated by *S. minutulus*, with a small interval dominated by *C. bodanica*. This suggests that most of this period had longer cooler springs that prolonged mixing, whereas a small interval (from ∼ 350 to ∼ 150 cal yr BP) was characterized by truncated spring mixing and intensified summer stratification (when *C. bodanica* dominates).

Table 3.3: Ecological requirements of dominant plankton diatom species in Crevice, Foy, Morrison, and Reservoir Lakes

Species	Ecological Preference of Dominant Plankton and Tychoplankton
A. formosa	Good P competitor, moderate Si competitor
C. bodanica	Low N specialist
C. michiganiana	Low nutrient specialist–Prefers well stratified waters
C. stelligera	Prefers shallow, warm, stratified water–Low nutrients
S. minutulus	Low Si:P specialist
Synedra tenera	Low P specialist

Foy Lake has two distinct diatom assemblages in sediments spanning the last 2500

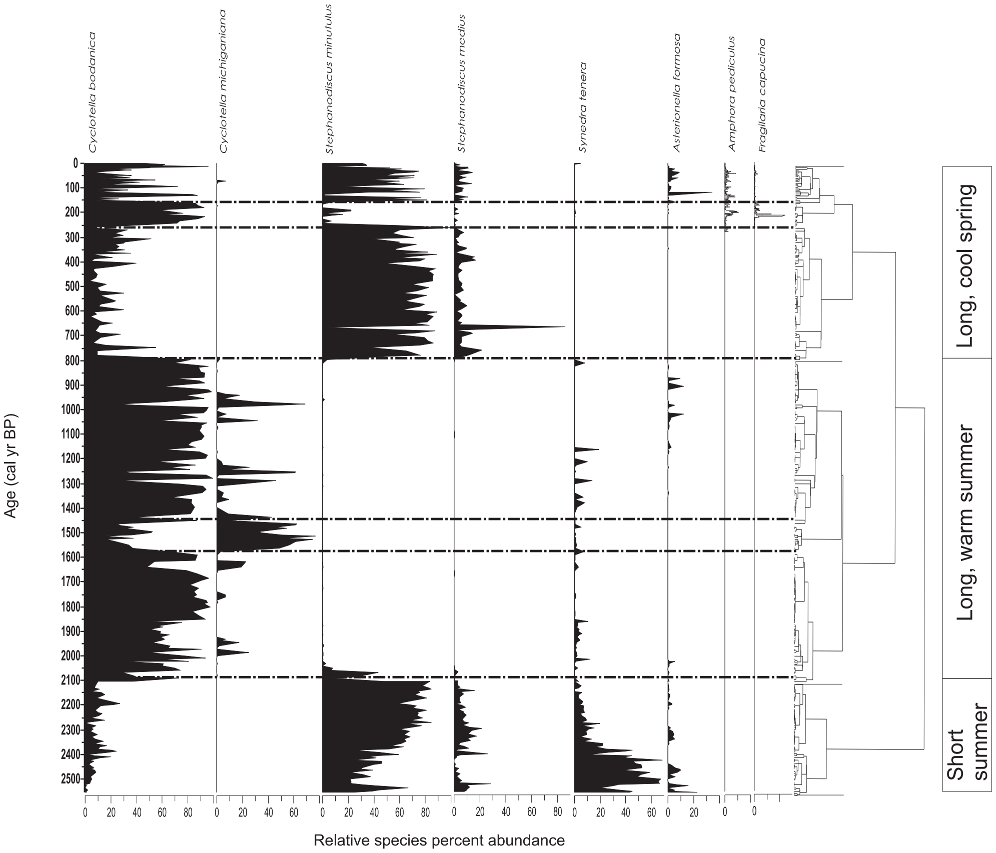

Figure 3.6: Crevice Lake diatom stratigraphy, cluster analysis, and climatic interpretation. The dashed lines are from cluster analysis. Short summer seasons persist from ~2500-2100 and 800-0 cal yr BP, while long warm summers predominate from ~2100-800 cal yr BP.

years (Figure 3.7). The period from 2650-1352 cal yr BP is dominated by the benthic species *Cymbella cymbiformis*, *Anomoeoneis costata*, *Encyonema silesiaca,* and *Craticula halophila*, which suggest that lake levels were lower than present at this time (Stevens et al., 2006). Also, *A. costata* first appears at 2200 cal yr BP, a species that has a high salinity tolerance (Fritz et al., 1993). This suggests higher salinity in the lake that results from evaporative concentration (negetative P-E), and thus very dry conditions. At several times between 1700 and 1400 cal yr BP, *C. bodanica* comprises approximately 40% of the assemblage for several decades. This deeper water, lower salinity species may indicate short periods of increased moisture and higher lake level. *C. bodanica*, a planktonic species, dominates the diatom assemblage from 1352-600 cal yr BP, which suggests lake level rise as a result of continual increases in effective moisture. After 650 cal yr BP, *C. bodanica* dominates, with several spikes of *C. halophila*, ($\sim$ 70, 450, and 650 cal yr BP) suggesting that overall lake level remains high, with a few very short intervals of lowered lake level. A model integrating diatom and isotopic data suggests that this interval reflects the wettest conditions of the 2600-year lake history (Stevens et al., 2006).

Morrison Lake has a highly variable diatom stratigraphy, with frequent alternations among the diatom taxa. Two major diatom assemblages dominate throughout the 3250 year record (Figure 3.8). The planktic genera *Cyclotella* and *Stephanodiscus* dominate from 3250-1150 cal yr BP and 600-0 cal yr BP. Multiple alternations, from *Stephanodiscus* to *Cyclotella*, such as those at 2150, 600, and 300 cal yr BP, occur throughout the record. Shifts in dominance of these two planktic genera imply fluctuations in the relative length of the spring and summer seasons, similar to the controls described for Crevice Lake. From 1150-600 cal yr BP a distinct appearance and dominance of *A. formosa* suggests several possible ecological drivers. Many recent studies (Schmidt et al., 2002; Wolfe et al., 2003; Saros et al., 2005) found that *A. formosa* increases or dominates during periods of nitrogen enrichment. *A. formosa* is also a high Si:P specialist (Tilman et al., 1982) that prefers higher N:P ratios (Kilham et al., 1996). In the Yellowstone region higher N:P ratios, resulting from increases in winter precipitation and spring runoff, combined a with relatively early onset of stratification, favor this species (Interlandi et al., 2003). This suggests that the interval from 1150-600 cal yr BP was warmer than the prior and subsequent periods and that winter precipitation was likely elevated.

Reservoir Lake consists of two sub-basins connected by a small shelf. From 2500-1700 cal yr BP, water level was quite low, as evidenced by several periods of diatom dissolution (2350-2330, 2170-2140, and 1910-1890 cal yr BP) and the predominance of *Cyclotella*

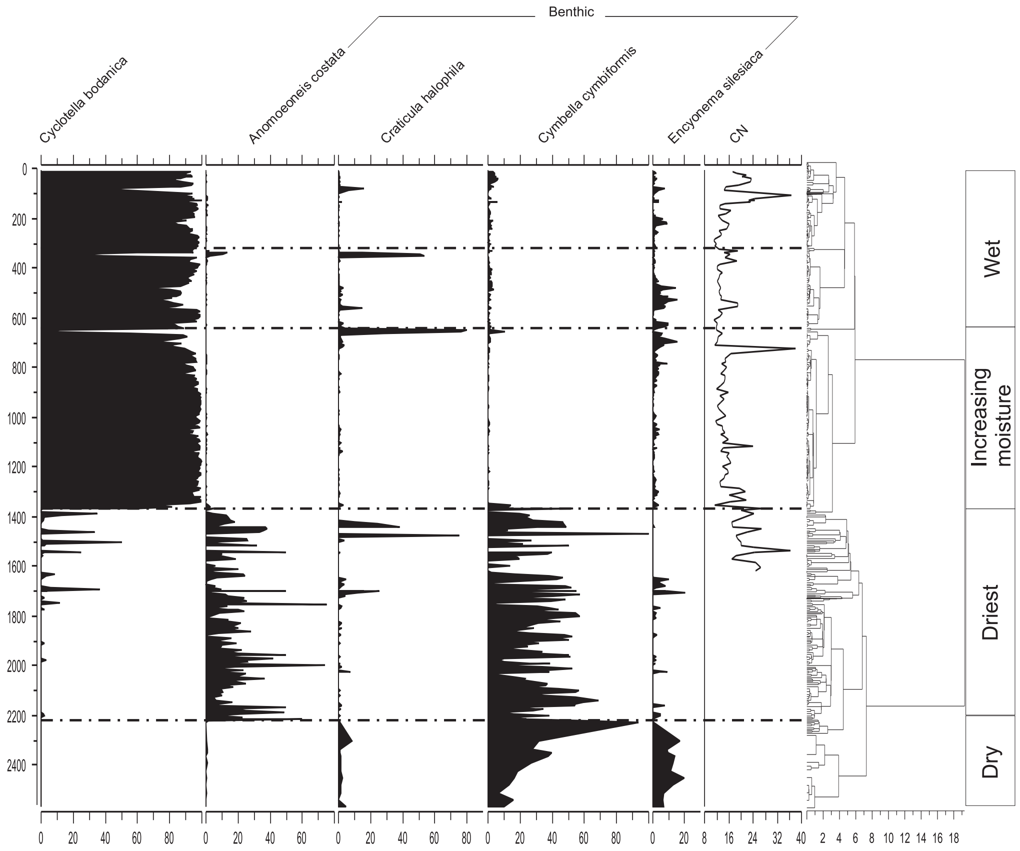

Figure 3.7: Foy Lake diatom stratigraphy, C:N analysis, cluster analysis, and climatic interpretation. The dashed lines are from cluster analysis. From 2650-2200 cal yr BP, lake levels are low, and the climate is dry, while 2200-1400 cal yr BP, lake levels decrease further, increasing the salinity level of the lake. 2200-1400 cal yr BP is the driest time during the previous 2600 years of lake history. From 1400-600, lake levels rise, indicating significant increases in moisture. From 600-present, lake levels are the highest throughout the record, except for several small droughts.

stelligera. This taxon is a shallow water tychoplankton that does well in warm, stratified waters with low nutrient conditions (Rühland et al., 2003) (Figure 3.9). From 1700-1390 cal yr BP Reservoir Lake shows several switches in community structure from *C. stelligera* to benthic species. The morphometry of Reservoir Lake suggests that an increase in benthics is an increase in water depth, as an increase in water depth submerges a large shelf that connects the two smaller basins (Figure 3.2). Additionally, *S. minutulus*, a planktonic

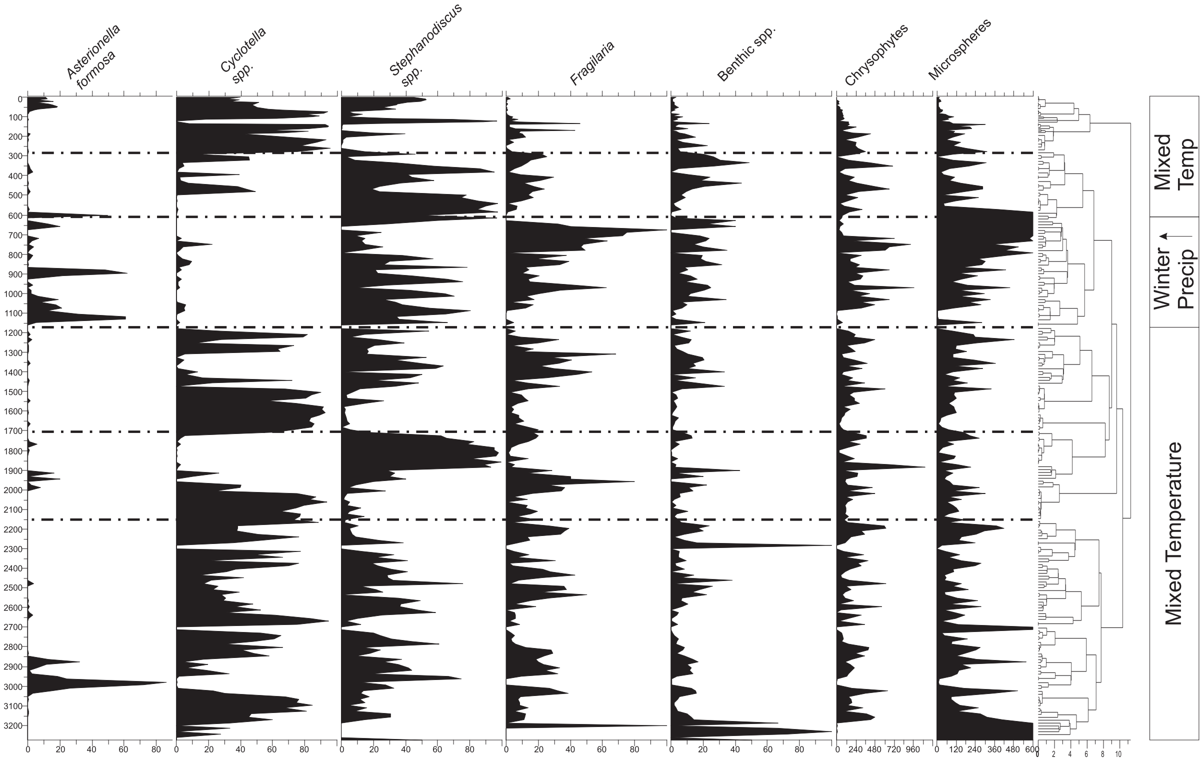

Figure 3.8: Morrison Lake diatom stratigraphy, cluster analysis and climatic interpretation. The dashed lines are from cluster analysis. From $\sim 3200 - 1150$ cal yr BP and 600-0 cal yr BP, the record shows rapid fluctuations from *Cyclotella* to *Stephanodiscus*, suggesting frequent changes in the length of the spring and summer seasons. From $\sim 1150 - 600$ cal yr BP the predominance of *A. formosa* suggests an increase in the winter precipitation.

species, becomes co-dominant with increases in benthic species, further supporting that an increase in benthic species results from an increase, rather than decrease in water depth. The intervals of *S. minutulus* dominance likely reflect years of high P availability because of extended spring mixing, as discussed previously. The period from 1390-890 cal yr BP shows a rapid rise and dominance of *A. formosa*, which may indicate an increase in Si:P and N:P, as a result of increases in winter precipitation and runoff likely elevated in nitrogen and silica inputs Theriot et al. (1997), whereas relatively early stratification favored lowered P availability (Interlandi et al., 2003). We interpret the lake level to be at the height of the shelf that connects the two sub-basins at this time. During this interval between 1390-

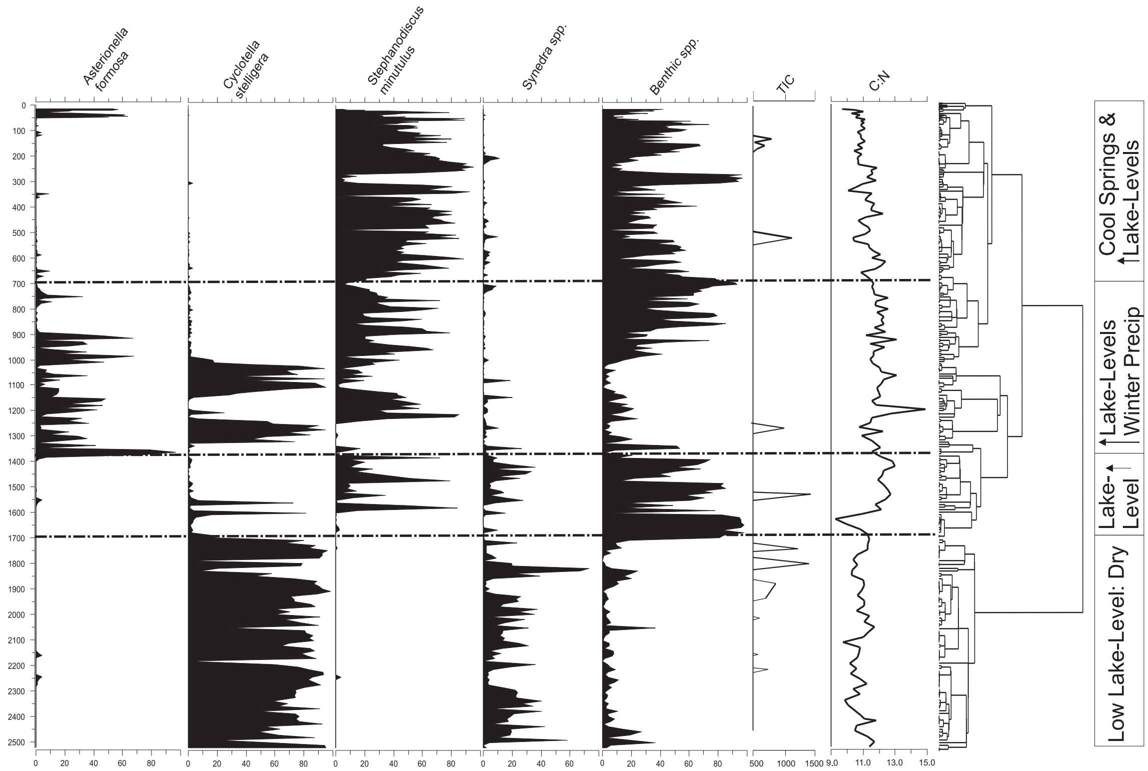

Figure 3.9: Reservoir Lake diatom stratigraphy, TIC analysis, C:N analysis, cluster analysis, and climatic interpretation.

800 cal yr BP, water depth is a control on diatom species composition, with decreases in water level favoring *C. stelligera* (shallow, warm waters) dominanted assemblages, while an increase in water depth leads to dominance of *S. minutulus* or *A. formosa*. During other periods, the co-dominance of *A. formosa* versus *S. minutulus* probably results from nutrient availability influencing the diatom community structure. Thus, frequent alternation among *A. formosa*, *C. stelligera*, and *S. minutulus* suggests that this may be a transitional time for the lake, where two main controls of diatom community structure exist, water depth and nutrient competition related to lake mixing/stratification. From 890-44 cal yr BP, the abundance of *S. minutulus* suggests that lake levels are sufficiently deep to support this species and that spring mixing is extensive, fostering the P-rich conditions necessary for

this species to bloom. Frequent fluctuations in the abundance of benthic species suggest changes in water depth, but that the lake level has not decreased sufficiently to separate the two sub-basins.

3.4.2 Regional Patterns

Large-scale shifts occur in all four lakes throughout the past 2500 years. Shifts that occur at approximately similar times in all lakes include changes in the intervals from 800-600 cal yr BP, 1350-1200 cal yr BP, 1700-1600 cal yr BP, and 2200-2100 cal yr BP (Figure 3.10). All lakes show limnological change at these intervals, but the nature of change is not the same in all basins. The earliest common interval of change is defined by cluster analysis at 2100, 2200, and 2150 cal yr BP for Crevice, Foy, and Morrison Lakes. While not included within the cluster analysis, the Reservoir Lake record shows severe dissolution from 2170-2140 cal yr BP and better preservation afterwards. During this interval, Crevice lake switches from a *S. minutulus* and *S. tenera* to a *C. bodanica* dominated assemblage, suggesting a shortening of the spring season and lengthening of the summer season. At this time in Foy Lake, *A. costata* first appears, which indicates particularly dry conditions within an extremely dry interval (Saros and Fritz, 2000). Morrison Lake shows a slow transition from *Stephanodiscus* to *Cyclotella*, which also suggests a seasonality change from long cool spring seasons to long warm summer seasons. Reservoir Lake shows severe dissolution within the diatom record during this time, which suggests significant decreases in effective moisture. Thus from 2200-2100 cal yr BP, Crevice and Morrison Lakes show a change in seasonality to warmer, longer summer conditions, while Foy and Reservoir Lake show evidence of significantly drier conditions, which could be a product of enhanced temperatures, decreased precipitation, or both.

The limnological changes seen at approximately 1700-1600 cal yr BP suggest a change in spring/summer seasonality that affects the duration of water column stratification at Crevice and Morrison Lakes, while both Reservoir and Foy Lakes show an increase in lake depth, which suggests elevated effective moisture. The shift in Morrison Lake from *Stephanodiscus*, which blooms during the spring mixing season, to *Cyclotella*, which blooms during summer stratification, suggests truncated spring mixing and more sustained summer stratification (Interlandi et al., 1999). The shift from *C. bodanica* to *C. michiganiana*, in Crevice Lake, similarly suggests a protracted summer season during this time. This suggests a climatic forcing that increased the length of the summer season in the regions surrounding Crevice and Morrison Lakes. The interval from 1700-1600 cal yr BP shows an overall increase in moisture for Reservoir Lake, whereas overall lake levels at Foy Lake are low. The first appearance of *C. bodanica* in Foy Lake, at approximately 1700 cal yr BP, suggests short-lived periods of increased moisture and higher lake levels. The differences in climate response suggest either a sharp climatic gradient or differential sensitivity of the lakes to different aspects of climate.

Between 1350-1200 cal yr BP, all four lakes show a rapid change in diatom community structure. Crevice Lake shows a transition from *C. michiganiana* to *C. bodanica*, suggesting a decrease in the duration of summer stratification. Morrison Lake shows the sudden dominance of *A. formosa*, suggesting an increase in winter precipitation and spring runoff. Foy Lake switches from a benthic dominated community to a planktic dominated community, as manifested in by the abundance of *C. bodanica*. This suggests an increase in lake depth and moisture. The Reservoir Lake record shows the sudden dominance of *A. formosa*, most likely resulting from increases in winter precipitation and spring runoff. Thus, overall this suggests cooler springs that reduced the length of thermal stratification, along with increases in winter precipitation at least at Foy, Morrison, and Reservoir Lakes.

The 800-600 cal yr BP change is a major shift in diatom species composition, which also marks the transition from the Medieval Climate Anomaly to the Little Ice Age in North

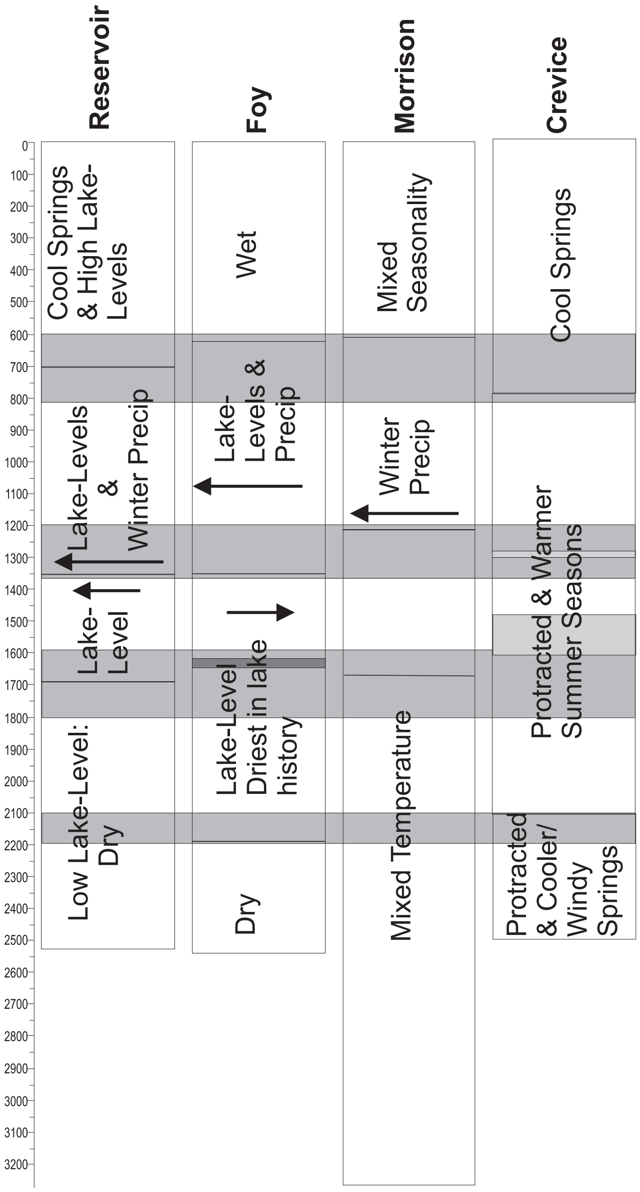

Figure 3.10: Schematic diagram showing the similarity in timing of environmental changes between the four lakes that occur at 2200-2100, 1700-1600, 1350-1200, and 800-600 cal yr BP. The black bar, 1700 cal yr BP, within the Foy Lake plot denotes the first appearance of *C. bodanica*, which indicates a short-lived, but significant climatic change to wetter conditions, and coincides with significant changes in the records of the other three lakes. The grey bars within the Crevice Lake record signifies dominance of *C. michiganiana*, which suggest even warmer conditions during this warm period.

American systems. The 800 cal yr BP shift in Crevice Lake, from a *Cyclotella* to *Stephanodiscus* dominated system, suggests a marked change in temperature seasonality, from protracted summer seasons to truncated summer seasons (Interlandi et al., 1999). Morrison Lake shifts from an *A. formosa* dominated assemblage to a *Fragilaria* and *Stephanodiscus* dominated system. This represents a change in seasonality characterized by shorter periods of stratification, possibly associated with a reduction in both winter precipitation and N inputs in runoff. In Reservoir Lake, the 890 cal yr BP shift from *C. stelligera* and *A. formosa* to *S. minutulus* and other benthic species suggests that the lake remains moderately deep, in addition to a lengthening of the spring season. Foy Lake shows a spike of *C. halophila* at approximately 625 cal yr BP. Stevens et al. (2006) interpret this benthic spike as a modest rise in lake level. Thus, Crevice, Morrison, and Reservoir Lakes show a transition to protracted spring and truncated summer seasons, while Foy Lake shows a moderate increase in effective moisture.

Crevice and Morrison Lakes also show similarities in the nature and timing of their diatom stratigrahies during the last 600 years that are not seen in the other lakes. At approximately 250 cal yr BP, both Crevice and Morrison Lakes switch from a *Stephanodiscus* to a *Cyclotella* dominated assemblage. *Cyclotella* dominates for 100 years at Crevice Lake and 150 years at Morrison Lake. The shift to *Cyclotella* may represent the culmination of the Little Ice Age in this region and climatic warming in spring and summer. After this, both lakes show some co-dominance and frequent alternations between *Stephanodiscus* and *Cyclotella* that are not previously seen in the record. This suggests that Crevice and Morrison Lakes are responding to environmental or climatic conditions that are different from the rest of the 2500-3000 year lake histories.

3.4.3 Forcing of Regional Climate Change

The similarities in the timing of change among the four lakes suggests that regional scale climatic change is largely responsible for the major changes in diatom community structure. The potential large-scale mechanisms that could cause some of these climatic variations include solar variations, sea-surface temperature anomalies, jet-stream displacement, trough circulation anomalies, and strength of the westerlies. Most of the mechanisms are inter-related variations in the expression of large-scale atmospheric circulation patterns. Variations of sea-surface temperatures in both the Pacific and Atlantic Oceans are associated with variations in Rocky Mountain precipitation, temperature, or seasonality. These variations include oscillations, such as Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) (McCabe et al., 2004).

The spectral analysis suggests a number of common frequencies amongst the lakes. The most common frequency or set of frequencies for all four lakes is 50-62 years (Figure 3.5). This frequency is commonly associated with the Pacific Decadal Oscillation (PDO). Another frequency, found in Crevice, Foy, and Reservoir Lakes is in the 34-42 year band, which is associated with the Atlantic Multidecadal Oscillation (AMO) (Knight et al., 2006). Recent research suggests that Atlantic SST anomalies are highly correlated with North American drought (McCabe et al., 2004; Sutton and Hodson, 2005). Feng et al. (2008) suggest that SST anomalies in the Atlantic and Pacific oceans may have caused the severe droughts throughout the northern Great Plains during the Medieval Climate Anomaly. They suggest that warm Pacific SST anomalies intensify the drought, while cool Atlantic anomalies extended the size of the afflicted region. Other research connects paleodroughts in the Rocky Mountain region to the PDO (Stone and Fritz, 2006; Tian et al., 2006). The correlation of Rocky Mountain lake behavior with periodicities evident in both Pacific and Atlantic SST records suggests that different drought periods might be more heavily influenced by the Atlantic versus the Pacific, suggesting that both oceans are instrumental in studying North American drought (McCabe et al., 2008).

Changes in the location and/or strength of high/low pressure centers cause displacement of the jet stream, and changes in the strength and position of high and low pressure systems affect overall atmospheric circulation (Oglesby and Erickson III, 1989; Laird et al., 2003; Booth et al., 2006a). As jet streams typically form between air masses of significantly different temperatures, precipitation, etc, this has large climatic implications. For southwestern Montana lakes, northward displacement of the jetstream commonly produces drier conditions. The offset and movement in jetstream displacement may explain why the hydrologic signals between Reservoir and Foy Lakes sometimes coincide, while during other periods, the two seem to have different climatic forcing.

Strength of the summer westerlies also has been associated with drought in the Northern Rockies and Great Plains regions (Booth et al., 2006a). This correlation was quite strong for the megadrought that occurred during the MCA (Bryson, 1966; Booth et al., 2006b). Sridhar et al. (2006) suggest an inter-related mechanism in which a change in wind direction cut off the precipitation supply from the Gulf Coast to the High Plains, resulting in severe drought during the MCA. While this study region is considerably west of the High Plains, in a similar fashion, the loss of precipitation from the Gulf could affect some portions of Montana's climate, particularly the northern range of Yellowstone.

3.5 Conclusion

Throughout the previous 2500 years, the western Montana lakes studied here, Crevice Lake, Foy Lake, Morrison Lake, and Reservoir Lake, have undergone significant shifts in diatom community structure. The lakes show synchronous timing of changes in the diatom stratigraphy at four separate intervals: 2200-2100, 1700-1600,1350-1200, and 800-600 cal yr BP. At 2200-2100 cal yr BP, Crevice and Morrison Lakes shift from long cool spring seasons to warm protracted summer seasons, while both the Foy and Reservoir Lake core records suggest extremely dry conditions. At 1700-1600 cal yr BP, Crevice Lake shows further intensification of summer stratification, likely resulting from longer, warmer summer seasons. Morrison Lake switches from *Stephanodiscus* to *Cyclotella*, suggesting a change to longer warmer summers, as well. Both Foy and Reservoir Lakes show increases in lake-level, resulting from moisture increases. In the interval from 1350-1200 cal yr BP, large increases in winter precipitation and spring runoff occur at Foy, Morrison, and

Reservoir Lakes, whereas Crevice Lake shows a slight decrease in the strength of summer stratification. From 800-600 cal yr BP, the North American Medieval Warm Period/Little Ice Age transition, the diatom record suggests an increase in the length of the spring season, with shortening of the summer season for Crevice, Morrison, and Reservoir Lakes. Foy Lake shows a slight increase in lake-level at this time.

Many of the shifts in diatom species distribution occur very rapidly, some within a few decades. The rapid nature of these changes suggests rapid shifts in climate. The diatom records of Crevice Lake and Morrison Lake reflect changes in the duration of spring mixing relative to summer stratification. Thus, these two basins are most sensitive to changes in the lake's energy balance and its seasonality, rather than shifts in the hydrologic budget (mostly due to the basin morphymetry). The diatom changes in Foy Lake and Reservoir Lake reflect changes in lake level, suggesting that these lakes respond most strongly to changes in the regional hydrologic budget.

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Chapter 4

Combining lake core records with the limnologic model DYRESM-CAEDYM to estimate climatic parameters during the Little Ice Age and Medieval Warm Period

Abstract

The Little Ice Age and Medieval Warm Period are two distinct climatic intervals evident in many North American paleoclimate reconstructions spanning the past 1000 years. Only a small number of paleoclimatic studies quantify climatic variation in these intervals, although a few estimate temperature and precipitation variation. The Crevice Lake, MT diatom paleorecord shows limnological responses inferred from fossil diatoms that reflect changes in temperature seasonality during the Medieval Warm Period, Little Ice Age, and modern periods. The core record, in conjunction with the model DYRESM-CAEDYM, provides a method to estimate climatic variables, during these two time intervals, including incoming solar shortwave radiation, cloud cover, temperature, vapor pressure, and wind speed by comparing the model simulated concentrations and distributions of diatom assemblages and comparing those outputs to the known ecological requirements of dominant diatom species. This study also explores the applicability of the DYRESM-CAEDYM model to paleo-based studies and the potential to further expand this type of coupled study.

4.1 Introduction

The climate of North America has shown a much greater degree of temperature variability throughout the late-Holocene than witnessed during the last century. Several studies have attempted to quantitatively reconstruct the range and timing of Holocene temperature and precipitation using sophisticated modeling techniques or biological indicators (Crowley and Lowery, 2000; Mann, 2001; Bradley et al., 2003). The Medieval Warm Period (MWP) and the Little Ice Age (LIA) are two well-documented periods of widespread anomalous climate during approximately the last 1,000 years. In many areas of North America, extreme moisture and/or temperature variation during these periods impacted biotic assemblages and/or ancient civilizations (Diaz and Stahle, 2007; Hunt, 2006). Current and future climate change may produce phenomena of a similar magnitude and impact ecosystems; therefore, it is important to understand the severity and character of the MWP and LIA (Diaz and Stahle, 2007). In some studies, semi-quantitative estimates of temperature and precipitation during the LIA and MWP have been generated from geochemical and biological indicators (Cronin et al., 2003; Shapley et al., 2005; Axford et al., 2009). In the northern Rocky Mountain region, quantitative reconstructions are limited to a small number of sites, but overall paleoclimatic reconstructions from multiple types of proxy data indicate a warmer climate during the MWP and cooler climate during the LIA, despite the high degree of spatial and temporal complexity of climate (Hughes and Diaz, 1994; Cook et al., 2007; Munroe, 2003; Koch et al., 2009).

Climate and weather are complex phenomena. Commonly, proxy data are used only for estimating past temperature and/or precipitation; most indicators are not suitable for quantitatively reconstructing other important climatic parameters, such as wind speed, vapor pressure, or solar radiation. Lakes often have highly-resolved sediment records, and their physical, biological, and chemical structure respond to multiple climate variables. These variables affect lake thermal structure and hence biological communities through several mechanisms (Bradbury, 1988). Modeling physical lake properties, along with biological indicators can provide a means both of quantifying temperature variation for additional parts of the northern Rocky Mountain region, as well as estimating the nature of variation in other climate variables, such as incoming solar radiation and wind. We explore that potential here.

4.1.1 Study Area

Crevice Lake (lat. 45.0° N, long. 110.578° W, elev. 1713 m) is located within the northern portion of Yellowstone National Park (YNP) (Figure 4.1). It is a closed basin, sub-alpine, mesotrophic lake. The lake is small (7.76 ha) and 31 m deep, which results in seasonal to yearly anoxia that aids in the formation and preservation of annual laminations (varves). The Yellowstone River runs along the eastern edge of Crevice Lake, separated from the lake by glacial till. Significant groundwater interactions probably link the lake and the river (Whitlock et al., 2008). Open douglas fir, juniper, and pine forests along with brushgrasses surround the lake.

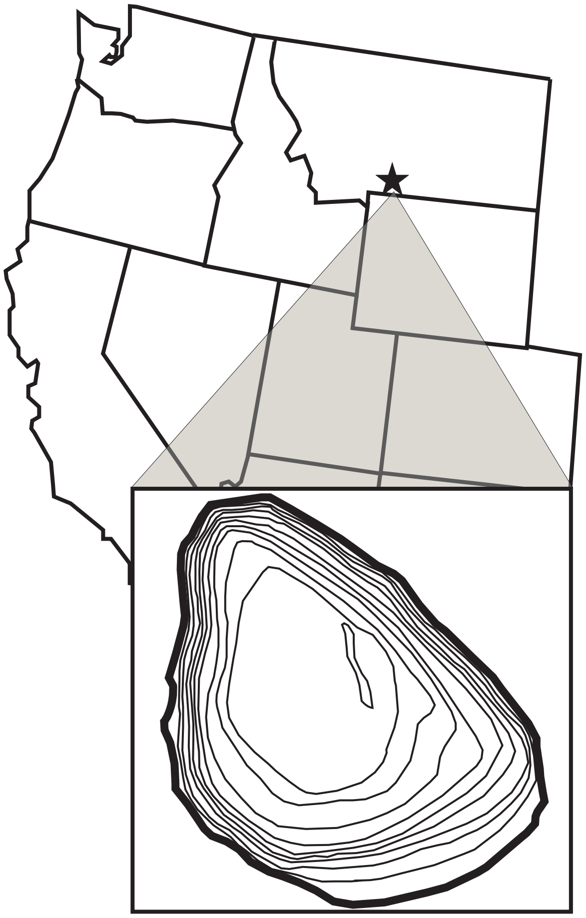

Figure 4.1: Locality and bathymetric map of Crevice Lake. Contour intervals are 3 m.

Western Montana climate is heavily influenced by the northeastern Pacific sub-tropical high pressure system and the strength and position of the jet stream (Whitlock and Bartlein, 1993). The northern portion of YNP (where Crevice Lake is located) is a summer wet/winter dry regime and receives most of its precipitation in the summer months from Gulf of Mexico moisture sources. In contrast, the southern portion of YNP receives the majority of its rainfall during the winter from westerly storm tracks (Whitlock and Bartlein, 1993). These precipitation regimes may be influenced by oceanic sea-surface temperatures (SST's) anomalies and their associated oscillations (McCabe et al., 2004; Sutton and Hodson, 2005; Feng et al., 2008; Stone and Fritz, 2006; Tian et al., 2006).

4.1.2 Crevice Lake History & Ecology

During the winter of 2002, Crevice Lake, MT was cored to provide a late-Holocene record of environmental change. The Crevice Lake core diatom record has three dominant assemblages, the *Cyclotella bodanica-Cyclotella michiganiana* assemblage, the *Stephanodiscus minutulus* assemblage, and the modern (co-dominated *C. bodanica* and *S. minutulus*) assemblage (refer to Chapter 3) (Bracht et al., 2008). A simplified diatom stratigraphy figure is included in Figure 4.2. During the MWP, the *C. bodanica* - *C. michiganiana* assemblage dominated. These species have low phosphorus (P) nutrient requirements, are nitrogen (N) specialists, and in Yellowstone region lakes often bloom just above the thermocline during the summer months (Interlandi et al., 2003, 1999; Kilham et al., 1996). Dominance of *Cyclotella* is favored during years with short spring seasons and extended warm summers that intensify the strength and duration of thermal stratification. During the LIA, the *S. minutulus* assemblage dominated. *S. minutulus* is a P specialist that blooms during years with long cool springs, which enhance and prolong water column mixing after ice-off, and the regeneration of P from the hypolimnion (Bradbury, 1988; Interlandi

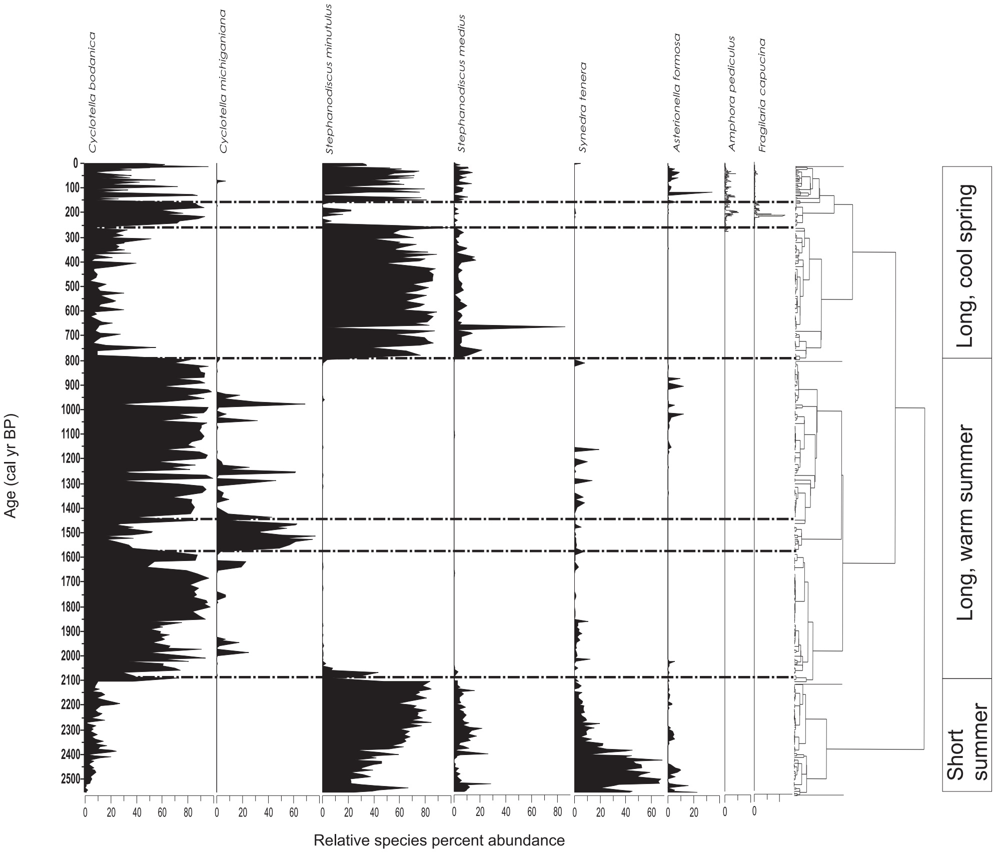

Figure 4.2: Crevice Lake diatom stratigraphy, cluster analysis, and climatic interpretation.

et al., 1999; Kilham et al., 1996). The modern assemblage of the past ∼ 150 years is co-dominated by two genera, *Cyclotella* and *Stephanodiscus*. For both *C. bodanica* and *S. minutulus* to dominate the assemblage, the lake must have moderate spring mixing and strong summer stratification to produce conditions favored by both *Stephanodiscus* and *Cyclotella* respectively. The modern assemblage suggests climatic conditions that are intermediate relative to the MWP and LIA. The Crevice Lake diatom biological indicator stratigraphy is useful for discerning differences in temperature seasonality, but does not provide quantitative estimates of the climatic variables that lead to these seasonal changes.

4.1.3 DYRESM-CAEDYM

DYRESM-CAEDYM (Dynamic Reservoir Simulation Model-Computational Aquatic Ecosystem Dynamics Model) is a thermodynamic-ecological coupled model that simulates lake thermal structure, chemistry, and biology, based upon weather, surface and groundwater fluxes, lake bathymetry, and initial lake conditions (Imberger and Patterson, 1981, 1990; Hipsey et al., 2006). The complexity of the model depends upon the number of model inputs and designated outputs. The model is one dimensional, with a layered Lagrangian scheme. It is a processed-based model, which does not require calibration. CAEDYM is a nutrient-phytoplankton-zooplankton model that is capable of modeling certain algal groups. The model is useful for forecasting the effects of climate change, nutrient loading, or other anthropogenic influences on lakes and their associated biological communities (Stasio Jr et al., 1996; Trolle et al., 2008). The model can simulate daily changes in lake thermal structure, salinity, water chemistry, nutrient concentrations, and diatom concentrations. The model is capable of running simulations on daily or sub-daily time-steps, which is useful, because many biological indicators, such as diatoms, respond at these scales to changes in their environment.

DYRESM-CAEDYM, in conjunction with the Crevice Lake, MT core record, provides an inverse modeling approach to quantify climate during the LIA or MWP. The objective of this study was to determine if this approach would prove useful and provide reasonable estimates of past climate variations. Therefore, the estimates provided in this paper are non-unique, and the number of model simulations is not exhaustive. The fossil diatom record from Crevice Lake changed distinctly at the MWP-LIA transition (800 cal yr BP) and at the culmination of the LIA (250 cal yr BP) and suggests major changes in lake thermal structure at these times. Different diatom assemblages were associated with each climate regime as described above. By adjusting climate parameters in the model to simulate paleoclimatological conditions, we are able to model the thermodynamic structure of the lake, and use this to estimate diatom abundances and distributions based on what we know about their ecology. By adjusting the inputs such that the outputs match the autecology of the dominant diatom species found in the sediment record, we were able to generate quantitative estimates of a combination of climatic variables, including temperature, incoming solar radiation, cloud cover, precipitation, vapor pressure, and wind speed during both the MWP and LIA for the Crevice Lake region.

4.2 Methods

4.2.1 Weather Data & Lake Temperature

Weather data (June 26- October 1, 2007) and lake thermistor data (June 2007- July 2008) were collected from the Crevice Lake watershed for model calibration. The weather data were collected using a HOBO weather monitoring station that contained sensors for incoming shortwave radiation, temperature, relative humidity, precipitation, wind direction, and wind speed. Measurements for all weather sensors were taken at 3 minute intervals, which were then averaged to hourly and daily measurements. The wind speed and direction sensor malfunctioned; therefore, we used daily wind speed averages from the Bozeman Gallatin Airport (NOAA). Lake thermal structure data were collected using a chain of HOBO Pro v2 water temperature data loggers, placed at the deepest location in the lake. The thermistors were spaced at 1 m intervals from the water surface to 12 m, 2 m intervals from 12 to 20 m, and 3 m intervals to the lake bottom (31 m). Temperature measurements were taken every 10 minutes and averaged to hourly and daily values. During deployment of the water temperature loggers, measurements of temperature, pH, specific conductivity (SpC), salinity, total dissolved solids (TDS), total dissolved gasses (TDG), and dissolved oxygen (DO) were taken using a HydroLab.

4.2.2 Model Setup

The DYRESM-CAEDYM model is actually two models coupled together. DYRESM is a one dimensional hydrodynamic model, and CAEDYM is an aquatic ecological model. It is necessary to calibrate the model so that the DYRESM temperature outputs are consistent with field observations, in order to confidently obtain a modern approximation of nutrient and diatom dynamics within the lake. To accurately model lake hydrodyamics, the model requires detailed bathymetric information that quantifies how the lake surface area changes with depth. A detailed bathymetric map and Surfer 8 were used to make these calculations. The model inputs include surface inflows, outflows, and initial temperature, chemistry (i.e. phosphorus, nitrogen, dissolved oxygen, and silica) profiles of the lake. The inflow and outflow inputs were made negligible in the model simulations. The initial conditions for temperature and water chemistry are shown in Figure 4.4. Other model inputs include a meteorological file; these meteorological variables were either directly measured from the HOBO field station, calculated from those measurements, or taken from the Bozeman Gallatin Airport dataset. The meteorological inputs include incoming solar radiation, cloud cover, air temperature, vapor pressure, wind speed, and precipitation. The weather collection at the lake meteorological station began June 26, but many of the diatom species competitive interactions occur directly after ice-off, which occurs earlier in most years. Therefore, the 2007 weather dataset was extended from June 26-October 1 to May 1-October 1. The records were extended by using the mean weather measurements from Gardiner, MT, Gallatin Airfield Bozeman, MT, and Mammoth Hot Springs, WY. We extended the weather record to May 1, as this is approximately one week after complete ice-off (with no sign of new lake ice formation) for the 2008 spring season. The record does not include the ice-off transition, as the current version of DYRESM-CAEDYM is not capable of modeling ice.

As no data are available for the groundwater interactions surrounding Crevice Lake, groundwater interactions are assumed to be negligible within the model. This is not realistic given the location of the Yellowstone River, but the absence of groundwater data prevents realistic estimates of groundwater fluxes (Almendinger, 1990; Whitlock et al., 2008). As the temperature of the hypolimnion remains constant throughout the year, it is unlikely that groundwater fluxes significantly impact the lake thermal structure. Surface water grab samples and HydroLab measurements provided the necessary water chemistry information for initial input files for CAEDYM. These include measurements of temperature, salinity, dissolved oxygen, pH, specific conductivity, and total dissolved solids. Water chemistry analysis included phosphorus, nitrogen, silica, and carbon concentrations. Sensitivity analysis was performed on several physical and biological parameters. Each parameter was varied within the measured ranges while keeping all other variables and parameters constant.

4.2.3 Development of LIA and MWP Weather Data

The MWP, LIA, and modern Crevice Lake diatom assemblages are quite distinctive and suggest different mean climatic conditions. The Crevice Lake MWP diatom assemblage is associated with a well stratified water column with long warm summers (*Cyclotella* dominated), the LIA diatom assemblage with extended isothermal mixing during long cool spring seasons (*S. minutulus* dominated), and the modern has moderate spring and summer seasons (co-dominance). To estimate the climatic conditions that caused the nutrient and mixing requirements that lead to dominance by *Cyclotella*, *Stephanodiscus*, or both, we generated several different weather scenarios. These weather scenarios produce the lake conditions necessary for *Cyclotella* or *S. minutulus* dominance or contemporary between the two species. The first modeling scenario is the modern contemporary environment, and this was carried out with contemporary meteorological measurements to see how well the model simulates modern conditions. The second modeling scenario simulates possible weather conditions during the LIA, while the third scenario simulates conditions during the MWP. Multiple simulations were run to test the model sensitivity to certain parameters, such as temperature, mixing depth, diatom concentration, etc. This sensitivity testing was done to evaluate the range of climatic or environmental variation required to change the diatom assemblage from a *Stephanodiscus, Cyclotella*, or co-dominant lake.

At this time, the model is not setup to estimate *Stephanodiscus* or *Cyclotella* abundances directly, but we infer which species is dominant based upon the ecology, timing of each species bloom, preferred depth, etc. In other words, we looked for changes in timing and depth distribution of diatoms that mimic the distribution of *Stephanodiscus* (throughout the mixed layer) or *Cyclotella* (along the thermocline). Each resultant set of temperature, nutrient, and diatom concentration output profiles were then compared to the known ecological preferences (season, depth, nutrients) of the each species to determine whether *Stephanodiscus* or *Cyclotella* was the dominant species in each modeling scenario.

We developed a simplistic weather generator to generate May 1- October 1 weather input datasets for the modern contemporary, MWP, and LIA scenarios. Once datasets were identified that produced diatom concentration plots that would infer each of the three species scenarios, datasets were manually adjusted in attempt to understand the potential range of each variable necessary to produce the desired diatom outputs. Initial model diatom concentrations were varied between $0.3-0.7\mu g/L$, as times that are *Stephanodiscus* dominated would have higher diatom concentrations after ice-off than when the species did not bloom. These initial diatom concentration estimates were limited, as the data do not exist to estimate diatom concentrations directly following ice-off.

4.3 Results

4.3.1 Field Data

The meteorological station data at Crevice Lake show air temperatures that differ from the surrounding Gardiner, MT and Mammoth Hot Springs, WY weather stations. Average daily meteorological station temperature ranges from 1.8-26.5 °C, average RH from 21-88%, pressure 817-838 mbar, solar radiation 70-313 W/m^2, and precipitation from 0-17 mm/day. Average daily values are in Figure 4.3. Depth profiles of DO, TDS, pH, SpC, and salinity are shown in Figure 4.4.

The thermistor field data for June 26, 2007-October 1,2007 are shown in Figure 4.5a. The lake temperatures display a typical lake stratification pattern, with development and deepening of the thermocline throughout the summer. The lake thermal structure begins to weaken towards the end of the meteorological record during the transitions from summer to fall. The DYRESM temperature outputs are shown in Figure 4.5b. The model effectively simulates the timing and development of the thermocline. To calibrate the model, the thermistor data from June 26 to October 1, 2007 were compared to model simulations of lake thermal structure. The modeled temperature output and the field thermistor data are within 2.5° C throughout the entire season (Figure 4.5c).

4.3.2 Model Simulations

We modeled three different climate/lake temperature scenarios, including one for each dominant diatom mode: modern, LIA, and MWP, as observed in the fossil record. Table 4.1 shows the average values for all the climate variables for both the meteorological station and the model simulations. This table shows that the range of individual climate variables throughout the entire growing season is not substantial from one scenario to the

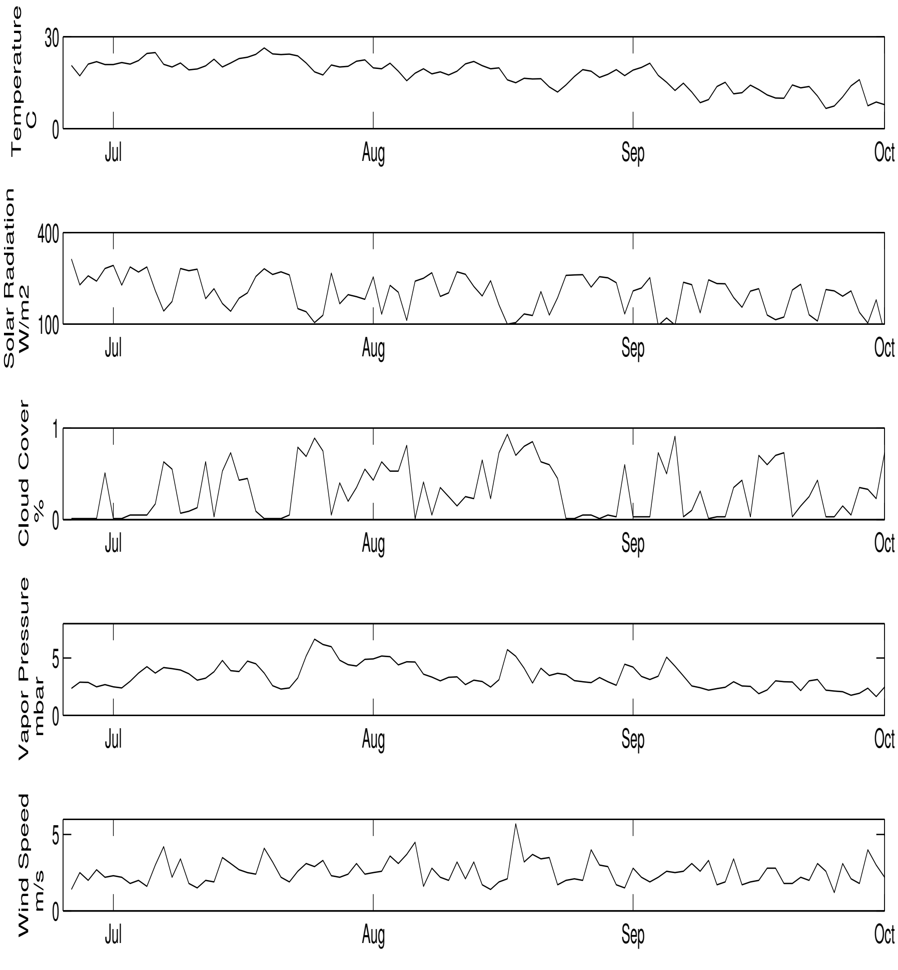

Figure 4.3: Meterological station data for the summer of 2007. The station was located on the southeast side of the lake.

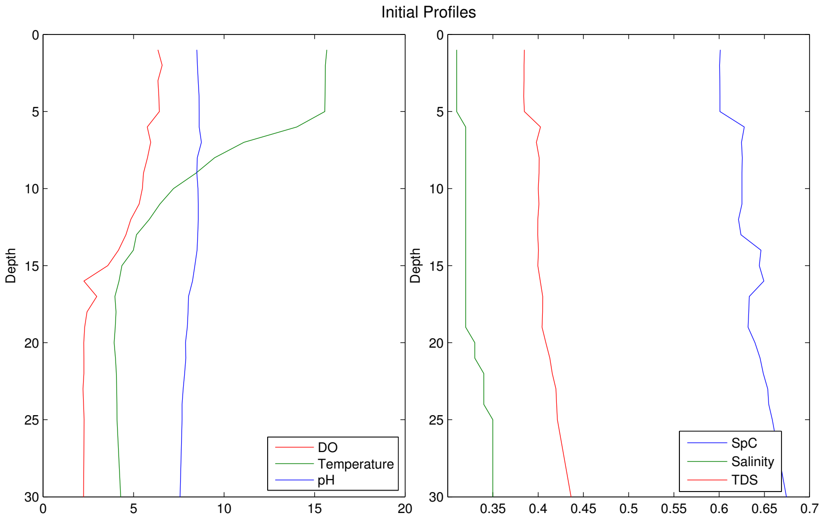

Figure 4.4: Depth profiles of temperature, DO, pH, salinity, TDS, and SpC taken with the HydroLab on June 26, 2007.

next; however, the values do vary considerably during the spring and early summer.

The modern Crevice Lake diatom assemblage is codominated by both *S. minutulus* and *C. bodanica,* as evidenced in the Crevice Lake freeze core spanning the last 2500 years (Bracht et al., 2008). Assuming that modern climatic conditions are conducive to lake conditions that foster codominance of *S. minutulus* and *C. bodanica*, we use these conditions and the June 26-October 1 weather data as a control. This scenario produces diatom concentration patterns that show diatoms within the eplimnion during June and high diatom concentrations along the thermocline throughout June and July. Based on the literature (Interlandi et al., 1999; Kilham et al., 1996), this is the pattern expected during contemporary times.

As many diatom species interactions occur immediately following ice-off, and because this period was not represented in the field measurements at the lake, the meteorological file (June 26-October 1) was replaced with a modeled dataset, extending the meteorological data through May 1-October (see 4.2.2). Climatic variable averages used to produce the

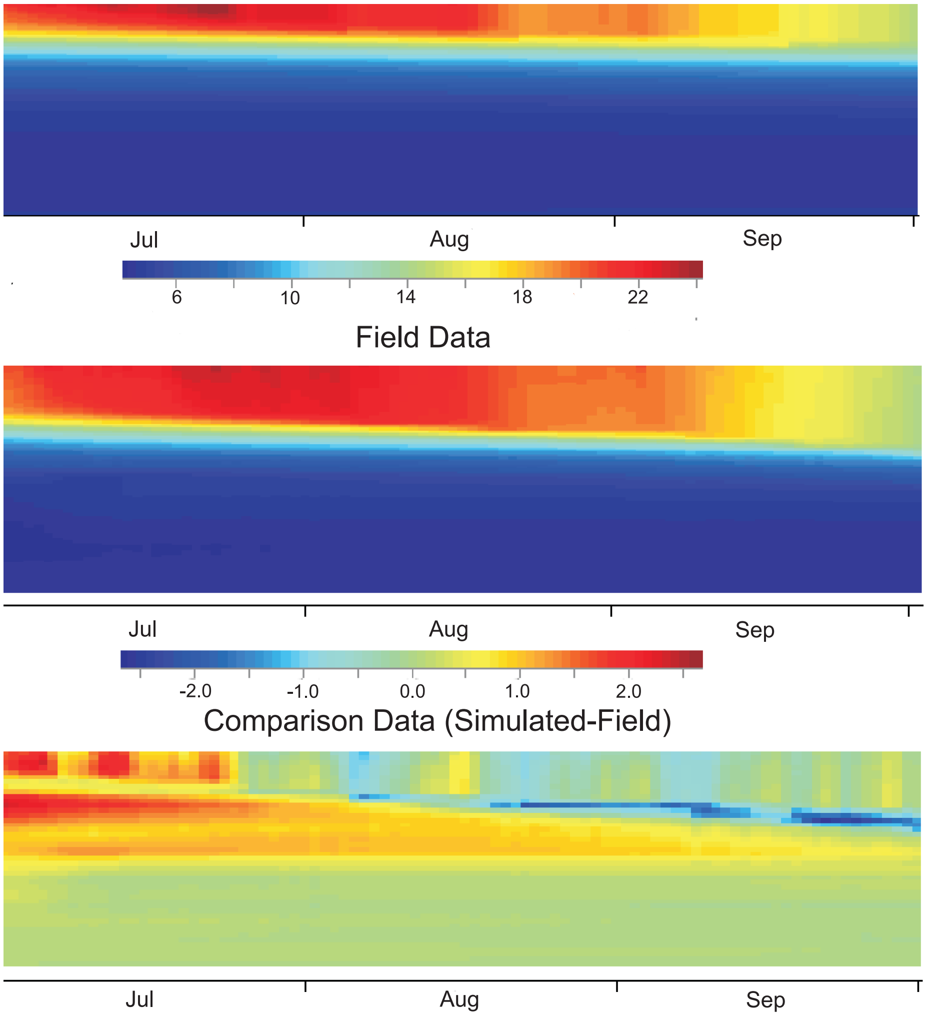

Figure 4.5: Comparison of field HOBO thermistor lake temperature data and the DYRESM-CAEDYM modeled temperature for the summer 2007. All temperature values are within ±2°*C* of measured values.

Table 4.1: Range of values of climate variables for May 1- October 1. The meteorological station data are the average of each variable from June 26- October 1. SW is shortwave radiation (W/m^2), CL is cloud cover (%), Temp is temperature (°C), VP is vapor pressure (hPa), and Wind is wind speed (m/s). The meterological station averages range from June 26- October 1.

June 26-Oct. 1					
Scenario	SW	CL	Temp	VP	Wind
Met. Station	199.58	.44	17.40	3.41	2.54
Contemporary	199.54-200.22	.44-.47	15.97-18.58	3.41-3.43	2.54- 2.62
LIA	189.23-196.4	.35-.46	15.33-15.64	3.20-3.40	2.58-2.71
MWP	199.82-200.41	.31-.45	17.0-17.45	3.28-3.41	2.55
May 1- Oct. 1					
Scenario	SW	CL	Temp	VP	Wind
Contemporary	190.52-205.71	.40-.47	15.02-17.02	2.8-3.41	2.7
LIA	179.29-189.3	.44-.54	13.99-15.12	3.42-3.63	3.15-3.31
MWP	206.38-213	.29-.46	17.65-17.94	3.18-3.63	2.6-3.15
May 1- July 9					
Scenario	SW	CL	Temp	VP	Wind
Contemporary	181.74-219.76	.43-.47	14.41-18.11	3.0-3.70	2.84-3.35
LIA	163.86-178.91	.45-.65	11.43-13.7	3.26-3.91	3.86-4.22
MWP	224.64-238.79	.30-.53	18.75-19.38	3.03-3.86	2.7-2.82

modern contemporary diatom assemblage are shown in Figure 4.6. Despite a wide range of variation in weather parameters, multiple runs of the model produced outputs consistent with the modern scenario. The contemporary simulation shows strong thermocline development by early June (Figure 4.7). The contemporary simulation shows lake temperatures similar to those seen in the 2007 summer thermistor data. The spring portion of the simulation shows values similar to those obtained during the 2008 ice-off transition and early spring. This suggests that the contemporary model outputs are equivalent to modern conditions. The model outputs for diatom concentration show high concentrations within the epilimnion during May, with lower diatom concentrations along the thermocline in June, July, and August. Again, this is the diatom distribution associated with contemporary.

LIA model outputs of temperature and diatom concentrations are shown in Figure 4.7b.

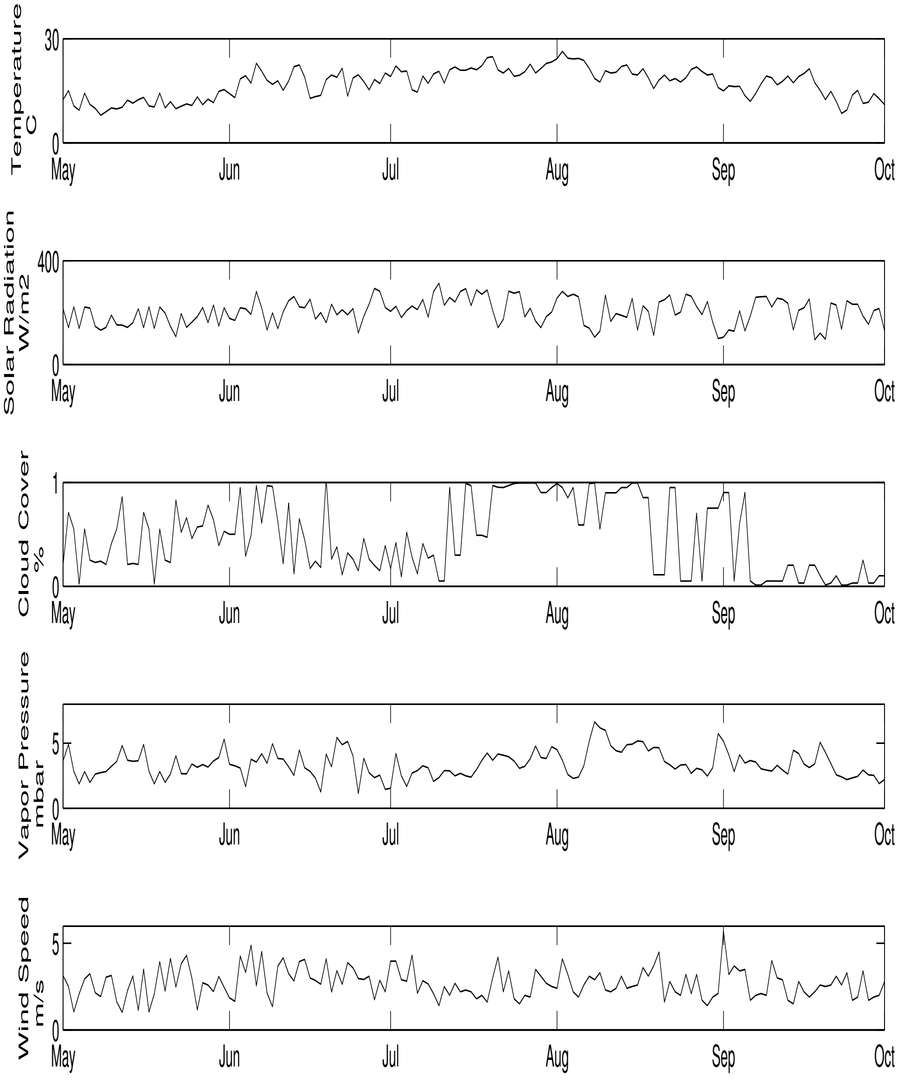

Figure 4.6: Weather parameters from one of the weather files used to simulate the contemporary diatom scenario.

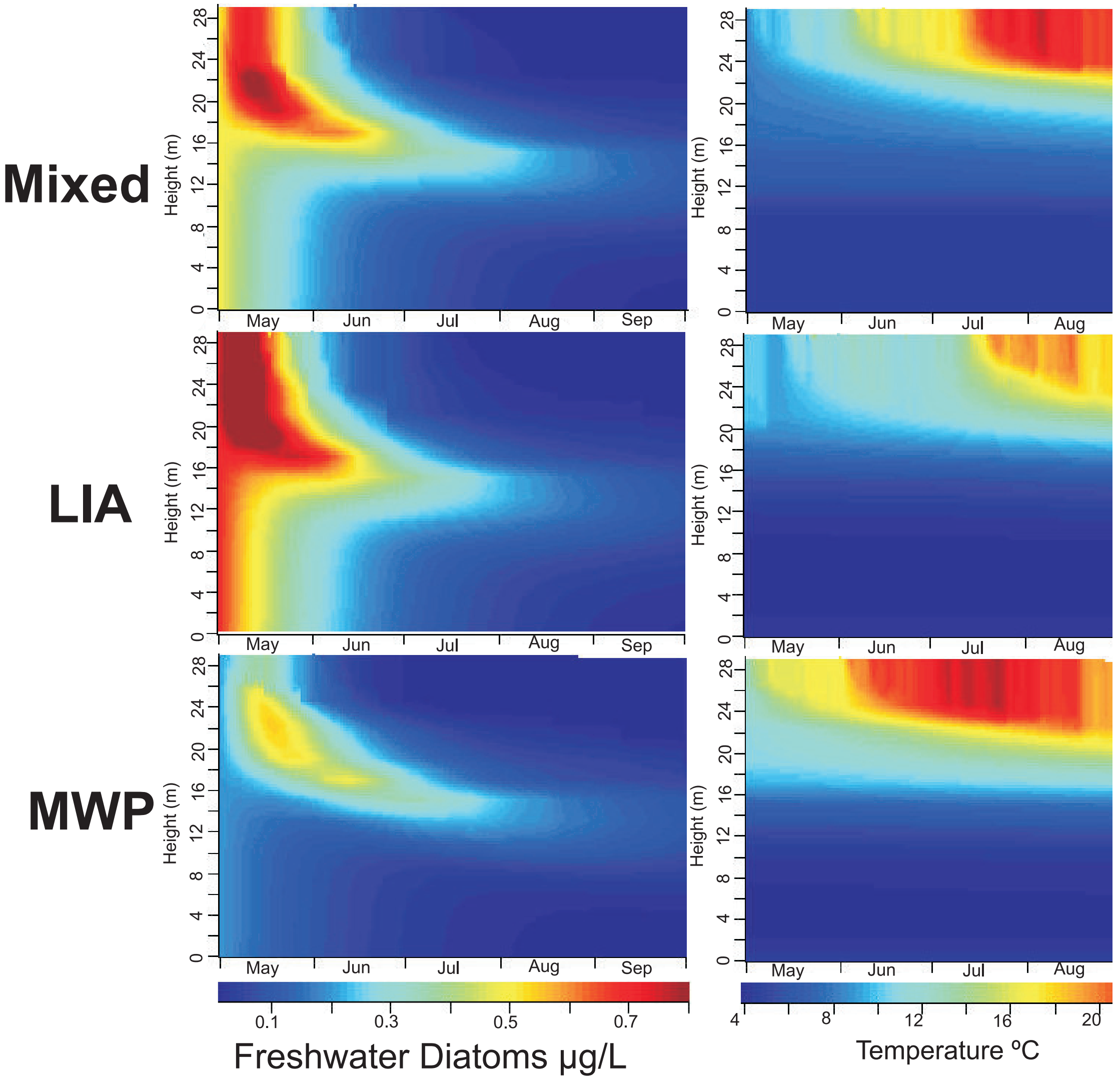

Figure 4.7: Diatom concentrations and temperature profiles for three modeling scenarios, a) the contemporary mixed diatom assemblage, b) the LIA *S. minutulus* dominated assemblage, and c) the MWP *Cyclotella* dominated assemblage

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The values of the weather parameters used to simulate the LIA are given in Figure 4.8. The greatest deviation of the climate variables from modern values occurs during spring and early summer (May 1- July 9); deviations occur at other times between May 1- October 1, but these are not as pronounced (the meteorological station uses the extended record). Values for incoming solar radiation and temperature are less than modern averages, while cloud cover, wind, and vapor pressure were greater. The isotherm plot shows hinderance of strong thermocline development until mid-July, although weak thermal structure is present much earlier in the season. The diatom output revealed high diatom concentrations in the epilimnion during the spring, with significantly decreased growth occurring near the thermocline during the summer. Upper waters were not depleted of nutrients or diatoms until June, as replicated by the model.

Weather parameter averages used for the MWP simulation are presented in Figure 4.9. Again, deviations from the control are most apparent in the comparison of values for the May 1- July 9 period, rather than the May 1- October averages. The isotherms show strong and early development of a thermocline, which is well established by mid-May. The DYRESM-CAEDYM model temperature and diatom concentration profiles for the MWP show diatom concentrations that were lower than in either of the other scenarios, and it lacks the May diatom bloom in the epilimnion. The majority of diatom growth, while limited, occurs along the thermocline, during May, June, and July (Figure 4.7c).

Sensitivity analysis shows that the diatom concentration outputs were not particularly sensitive to changes in the thermodynamic parameters (such as light extinction coefficient) of the model, but were sensitive to the changes in the ecological parameters. Figure 4.10 compares the effects of a sensitivity analysis of the light extinction coefficient, which shows an insignificant difference in the depth-averaged diatom concentration across a range of values. The figure also shows the effects of internal silica stores, which shows significant differences in the depth-averaged diatom concentration in simulations with different ini-

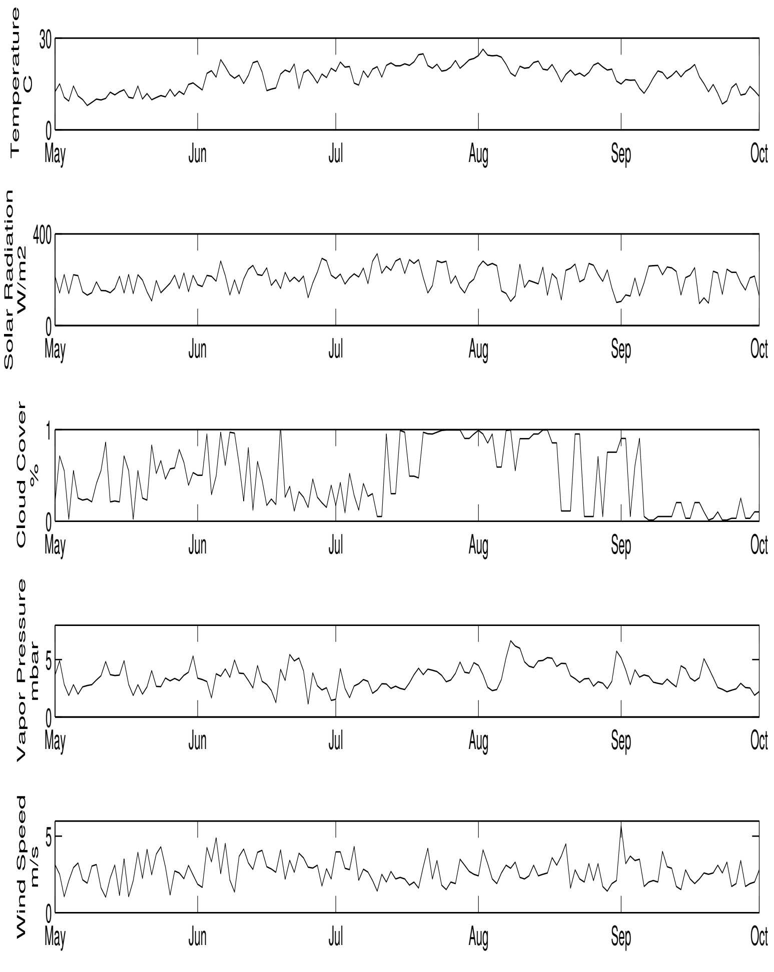

Figure 4.8: Weather parameters from one of the weather files used to simulate the Little Ice Age.

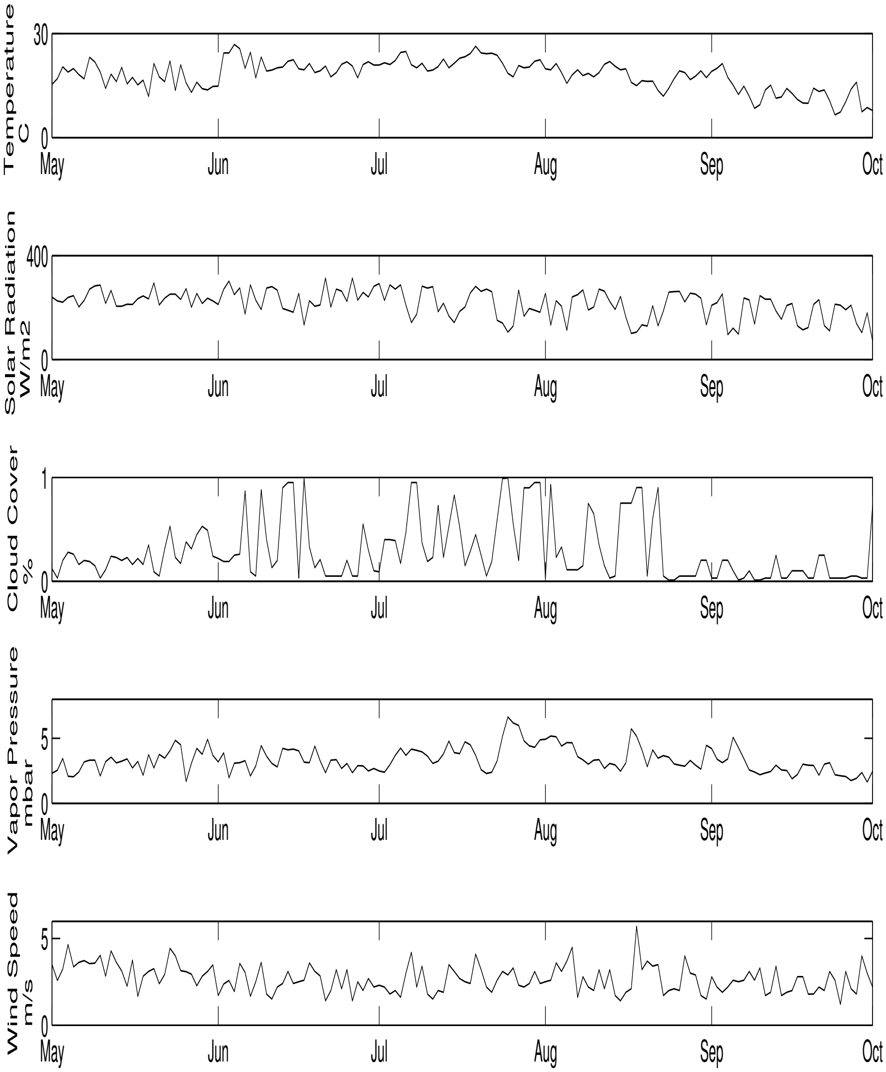

Figure 4.9: Weather parameters from one of the weather files used to simulate the Medieval Warm Period.

tial values. Changes in the critical wind speed showed results identical to that of the light extinction coefficient in other words changes in input values did not produce a distinct change in diatom concentration. The lack of sensitivity of physical parameters is expected due to model design (Imerito, 2007). The model also showed sensitivity to another ecological parameter, the half saturation constant, but less than the sensitivity caused by internal silica concentrations. The half saturation concentrations and internal silica concentration are extremely important in species resource competition and exert direct effects on the composition of diatom communities (Grover, 1997; Tilman et al., 1982). Therefore, it is not surprising that changing these variables within the model would lead to changes in the diatom outputs.

The sensitivity analysis results are similar to that of Schladow and Hamilton (1997), who found that phytoplankton phosphorus uptake kinetics, minimum internal concentration, the half saturation constant, and the maximum uptake rate had the largest effects on chlorophyll a concentrations within the model simulations. Schladow and Hamilton (1997) also found that phytoplankton growth rates, respiration, and mortality affected chlorophyll a concentrations. While chlorophyll a concentrations include all phytoplankton groups, diatoms concentrations should show similar patterns to those found in that study. The sensitivity of the model to ecological nutrient parameters suggests that the model could be tailored to model specific diatom species interactions, by adjusting the ecological parameters to fit individual taxa. Model sensitivity to parameters not considered also may alter the diatom concentration outputs, such as model sensitivity to re-suspension of nutrients from the hypolimnion. Increased understanding of model response to such parameters would increase confidence in interpretation of model outputs.

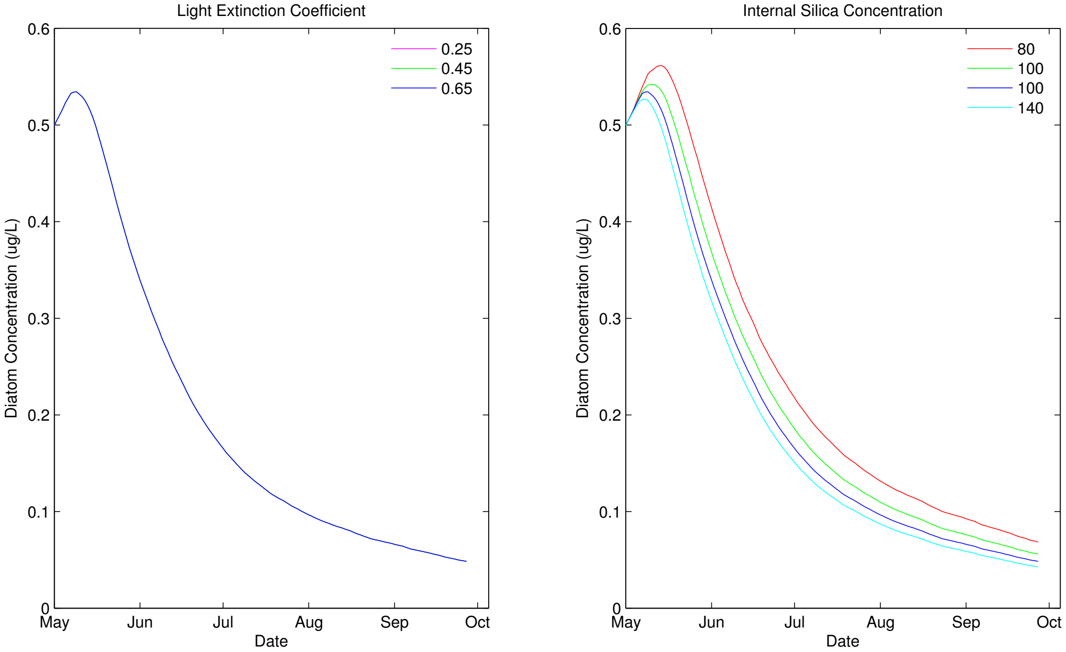

Figure 4.10: Results of the light extinction coefficient and internal silica stores sensitivity analysis.

4.4 Discussion

To test the sensitivity of our model to changes to single parameters, we attempted a number of model scenarios where individual parameters were altered. Despite some substantial adjustments, none of the variables were capable of significantly altering both the isotherm and diatom concentrations from the modern conditions. For example, by changing temperature by as much as ±10°, we were able to significantly change the stratification output, but little or no change was produced in the diatom concentrations or species composition/distribution. The climatic variable estimates from the model are not exclusive; changing different variables by different amounts may produce model results similar to those shown. The climate variable estimates presented in this paper include the the ranges of all weather parameters considered, most likely to produce the diatom concentrations associated with the lake core species. Large changes in temperature or solar radiation did not produce deviations from the modern isotherms that were as large as expected. However, changes in all variables were instrumental in altering lake thermal structure and thus diatom concentrations. This suggests that alterations in only one component of the climatic system are not likely to have produced the changes in lake dynamics during the LIA or MWP. This result points to the interdependence of multiple climate variables in affecting lake thermal structure and diatom species composition.

4.4.1 Contemporary Scenario

We changed lake and weather parameters in the model in an attempt to reproduce diatom concentrations, and hence interpreted assemblages, similar to those observed in the sediment archives. A wide range of modeled weather conditions were capable of producing patterns similiar to the modern lake state. The contemporary isotherm plot shows temperature profiles similar to those obtained from the 2007-2008 thermistor measurements. The diatom concentration plot displayed a moderate bloom in the epilimnion during May, with decreased diatom concentrations along the thermocline during June and July. The high diatom concentrations during May, within the epilimnion, are interpreted as *S. minutulus* blooms, as these species tend to bloom within the upper portion of the water column during the spring season. The lower diatom concentrations, along the thermocline during June and July are interpreted as *Cyclotella* blooms, as these species are known to grow along the thermocline during the summer months. Therefore, the contemporary assemblage of *Cyclotella* and *S. minutulus* should show moderate diatom concentrations in the epilimnion during spring, and lower, but still significant, concentrations along the thermocline during the summer months.

The contemporary simulation stems from a climate that resembles modern conditions;

as a result these climate variable averages should, and are, intermediate of the LIA and MWP values. The contemporary scenario and meterological station data averages are different, because the meterological station does not include data from May 1- June 25.

4.4.2 LIA

The Crevice Lake diatom record transitions from a *C. bodanica* dominated assemblage to a *S. minutulus* dominated assemblage at the beginning of the LIA. The LIA is a period of distinctive climate throughout much of western North America (Whitlock et al., 2008; Graumlich et al., 2003; Gray et al., 2007), characterized by a climate colder than modern and in some places high to moderate precipitation. The coincidence of change at Crevice Lake with major change regionally suggests that the environmental factors controlling diatom species interactions are a product of large-scale climate dynamics. The LIA isotherm plot shows hindered and weak development of a thermocline until mid-July. The weak thermocline allows continual regeneration of nutrients from the hypolimnion. These conditions favor the higher nutrient (P) requirements of *S. minutulus*. This is represented by the strong May bloom in the LIA diatom concentrations. A strong thermal gradient does not form until late in the simulation, because mixing occurs in the upper layers throughout July, which maintains higher nutrient levels, as shown by model outputs for phosphorus concentration (not shown). The weak development of a thermocline also implies that *S. minutulus* can bloom deeper in the water column, later into the summer. Figure 4.7 shows lower diatom concentrations along the thermocline throughout the summer. We interpret the mid-late summer thermocline diatom concentrations as *Cyclotella* blooms. As *Cyclotella* is always present when *S. minutulus* dominates in the Crevice Lake core record, this is expected. The range of values of the weather inputs that we interpreted as *Stephanodiscus* dominated assemblages is shown in Table 4.1.

4.4.3 MWP

During the MWP, proxy data suggest that the northern YNP region was considerably warmer and that droughts were frequent (Hadly, 1996; Gray et al., 2007; Whitlock et al., 2008). The Crevice Lake diatom record suggests prolonged warm summers during the MWP. The MWP diatom record is dominated by both *C. bodanica* and *C. michiganiana*. Short springs and warm summer conditions lead to early formation of a strong thermocline, which prevents regeneration of nutrients from the hypolimnion. The MWP isotherm plot shows this early and strong development of a thermocline, with the waters fully stratified by mid-May. The diatom concentrations lack a May eplimnion bloom observed in the other scenarios, but do show moderate diatom concentrations along the thermocline throughout May, June, and July. We interpret these diatom concentrations as *Cyclotella* blooms, as they occur along the thermocline (Interlandi et al., 1999). The range of values of the weather inputs that we interpreted as *Cyclotella* dominated assemblages is in Table 4.1.

4.4.4 Seasonality Effects

Table 4.1 shows the climate variable averages for three different periods of consideration. The June 26-October 1 and May 1- October 1 averages do not show obvious trends, as the Mixed simulation variables often have higher or lower values than either the MWP or LIA (the Mixed scenario should result from averages that are intermediate between MWP and LIA values). However, the spring and early summer period, May 1- July 9, shows distinct differences that are more intuitive. Thus, the contemporary scenario shows averages that fall between the LIA and MWP. This suggests that the diatom species within Crevice Lake are responding to changes in seasonality rather than growing season average change in climate parameters, as also suggested in several diatom-based paleoclimatic reconstructions elsewhere (Bradbury, 1988; Kilham et al., 1996; Talling et al., 2005; Köster and Pienitz, 2006).

The importance of seasonality in the regional diatom record suggests that diatoms are good indicators of seasonal changes in these montane environments, and that seasonality is extremely important when considering climate change. Moderately deep lakes, such as Crevice Lake, are often dominated by a few planktonic diatoms that tend to have seasonal blooms, and seasonality related changes (i.e., stratification, nutrients) drive these diatom populations. Many climate change studies (either forecasts or climate reconstructions) focus upon the yearly or decadal changes within a few climate parameters and may not capture fully the significant local drivers of change.

4.4.5 Model Limitations

The use of DYRESM-CAEDYM with the Crevice Lake core record does have several limitations. The most notable limitation is that this is an inverse modeling approach, with non-unique solutions. Another limitation is the methodology for generating weather datasets. Lack of site-specific variables for the model and short datasets (less than 1 year) prevented use of current weather generators. Therefore, the climatic variable estimates may be greatly improved with the use of a more sophisticated weather generator. Another large limitation is the lack of thermistor or weather data during the 2007 ice-off transition; logistics prevented instrument deployment during this time, so the 2008 ice-off data were used instead. The lack of an ice module for this lake in the model also prevented evaluation of species concentrations during the ice-off transition. Additionally, the model does not account for individual diatom species, but rather calculates values for this algal group as a whole (see section 4.2.3). Specifying the nutrient requirements of individual taxa, within the model, would show the concentrations of each taxa, rather than the total diatom concentration, which could lead to refinement of climate parameter estimates. Another model limitation is the lack of groundwater inputs in the model, but we do not believe that addition of these data would significantly alter model results.

The model estimates climatic parameters during the ice-free season of the lake. As such, the fall and winter seasons are not considered. It is important to note that the severity of the fall and winter seasons may significantly impact the environment and biota surrounding the lake, which in turn can affect lake biota. In other regional lakes, for example, paleodata suggest the input of nutrients in snowmelt may significantly affect lake dynamics. Therefore, the model only provides climatic parameter estimates during the ice-free season, but does not provide a complete seasonal or yearly estimate of climate.

4.5 Conclusions

The MWP and LIA are two distinct intervals of climate that differ from modern temperatures, precipitation patterns, and likely other climatic factors. Current proxy data, such as, pollen, isotopes, chironmids, and diatoms, provide qualitative or semi-quantitative estimates of temperature and precipitation, but quantitative reconstructions are few in number, and these are only two components of the climate system (Köster and Pienitz, 2006). Other variables, such as solar radiation, vapor pressure, cloud cover, or wind speed are important components of climate as well. Combining high-resolution diatom records from Crevice Lake, along with the coupled thermodynamic-ecological model DYRESM-CAEDYM, an estimate of average spring/summer conditions was obtained for various climate parameters, incoming solar radiation, cloud cover, temperature, vapor pressure, and wind speed, during both the MWP and LIA. Model outputs were created that mimicked the seasonality changes evident in the stratigraphic record. This may also suggest that changes in seasonality are a key component in understanding the regional characteristics of both the MWP and LIA. Specifically, it suggests that a combination of lower temperatures, cloud cover, and incoming solar radiation than modern interacted to affect lake thermal structure during the LIA, with temperature depressions several degrees lower than modern. The inverse set of conditions characterized the MWP, with temperatures and incoming solar radiation higher than modern.

This study also shows the combination of lake core records and the model DYRESM-CAEDYM may prove useful to estimate previous climatic variables. Although this study explores only changes in thermal structure, the model could also be tailored to other variables of interest, such as lake evaporation or lake-level. While this study is a cursory examination of this technique, we believe that this approach may be quite useful for future studies of the nature of past climate.

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Chapter 5

Summary

5.1 Conclusions

5.1.1 Major Findings

Lake response to climate change is influenced by a myriad of factors, many of which are co-dependent. Analytical models provide a method to analyze lake response to perturbations in the hydrologic or energy budget. The hydro-climate model developed in this thesis assesses the effects of changing the ratio of evapotranspiration to precipitation and land-use change on lake level. The model categorizes the lakes as permanent, ephemeral, or sensitive to vegetative change. The model can be used to identify lakes who have dominant controls other than precipitation, evapotranspiration, lake area, and basin area, by comparing lake plotting position to the theoretical lake categories. This may be a useful tool in paleoclimatic studies to identify both lakes that would be more likely to record changes in the hydrologic balance within their sediments and the lakes that are likely to preserve complete sediment records.

Different lakes may respond to different aspects of climate, including temperature, hydrologic balance, seasonality, etc, making inferences from a single paleoclimatic site difficult. Multiple high-resolution lake core records, within close geographic proximity, provide a means to separate local and regional influences on lake core records. In a comparison of four basins in the Rocky Mountains of Montana, multiple statistical techniques proved useful in determining local versus regional environmental or climate influence. Although the nature of limnological change varied among lakes, similarities in the timing of shifts in diatom species abundance suggest some level of synchroneity of the lake core records that are manifestations of large-scale climatic processes.

All four lakes show significant changes at four separate intervals: 2200-2100, 1700-1600, 1350-1200, and 800-600 cal yr BP. At 2200-2100 cal yr BP, Crevice and Morrison Lakes shift from protracted spring seasons to warm extended summer seasons, while both

Foy and Reservoir Lake core records suggest extremely dry conditions. At 1700-1600 cal yr BP, Crevice Lake shows further intensification of summer stratification, likely resulting from longer, warmer summer seasons. Morrison Lake switches from *Stephanodiscus* to *Cyclotella*, suggesting a change to longer, warmer summers, as well. Both Foy and Reservoir Lakes show increases in lake-level, resulting from moisture increases. In the interval from 1350-1200 cal yr BP large increases in winter precipitation and spring runoff occur at Foy, Morrison, and Reservoir Lakes, whereas Crevice Lake shows a slight decrease in the strength of summer stratification. From 800-600 cal yr BP, the North American Medieval Warm Period/Little Ice Age transition, the diatom record suggests an increase in the length of the spring season, with shortening of the summer season for Crevice, Morrison, and Reservoir Lakes. Foy Lake shows a slight increase in lake-level at this time. Southwestern Montana climate is most likely influenced by interactions amongst manifestations of both the Pacific and Atlantic Oceans, and spectral analysis of diatom data show periodicities consistent with both Atlantic and Pacific forcing.

These lake core records and lake models can be used in conjunction to refine estimates of past climate parameters. The Crevice Lake diatom core record provides qualitative evaluation of past climatic variability within the northern Rocky Mountains. However, it does not provide quantitative estimates of the climate variables that indirectly caused the changes in diatom stratigraphy. The model DYRESM-CAEDYM provides a method to estimate climate variables, incoming solar radiation, cloud cover, temperature, vapor pressure, and wind speed, during the Medieval Warm Period or the Little Ice Age.

5.1.2 Suggestions for Further Research

All three components of this dissertation could be expanded or improved. The hydroclimate model could include more lakes that are spatially spread over a greater area. The establishment of spatially coherent patterns could help identify geographic regions where the model is more applicable than others. Also, more lake-level or paleoclimate records could be included to the model.

All four lakes discussed in this dissertation have core records that extend beyond 3000 years. Currently, there is a collaborative multi-proxy effort to extend the Crevice Lake core throughout the Holocene. Charcoal and pollen analysis for Reservoir Lake has already been completed for the long core, but diatom and geochemical analysis could be extended, as well. The Morrison Lake diatom record could also be extended throughout the middle and early Holocene. Additionally, a comparison to Pacific and Atlantic sea-surface temperature or other records may help identify larger-scale forcing mechanisms of western Montana climate.

The DYRESM-CAEDYM model could be expanded by modeling climatic transitions other than the Medieval Warm Period and Little Ice Age. Inclusion of an ice module would model species interactions directly after ice-off, which is a crucial time in for species dynamics in the Yellowstone area lakes. Further research could also incorporate individual species requirements within the model to more accurately estimate previous climatic conditions.