DIATOM-INFERRED RECORDS OF PALEO-CLIMATE AND
PALEO-HYDROGEOLOGY FROM LAKES IN
REGIONS OF DIFFERENT CLIMATE

by

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A DISSERTATION

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ABSTRACT

I comparatively investigated mid-to-late Holocene paleo-climate and paleo-hydrogeology in three regions with different climates (Alaska, New Mexico, and Alabama) using diatom frustules as the primary proxy sampled from lake sediment cores. This cross-regional research differs from previous paleo-limnology syntheses because it was designed a priori to simultaneously decipher differential environmental conditions using uniform measurements of the same proxy types with equal environmental sensitivities across spatial scales. Data were analyzed with a combination of multivariate ordination and time series bandwidth analysis to identify significant bifurcation points between periods of changing environmental conditions.

Each study region demonstrated different environmental changes through time. Diatom community dynamics in Alaska were significantly correlated with temperatures, indicating that diatom community structure is a validated temperature change surrogate. In New Mexico, diatom dynamics were significantly correlated with both precipitation and solar intensity, suggesting that diatoms are validated surrogates of solar-modulated drought. Additionally, the diatoms indicated that the study lake was susceptible to drought-induced acidification. In Alabama, the combination of diatoms and sedimentary organic matter elucidated oxbow lake evolution and fluctuations in coastal plain water tables. These changes were potentially caused by alterations in precipitation and eustatic sea levels following the last glaciation. Similar interpretations of mid-Holocene hydrogeology have been reported elsewhere in the coastal plain.

This cross-regional research demonstrated differential proxy responses between each climate region. More importantly, it also suggested reasons why uniform methods elucidated
varying responses across broad spatial scales. Global climate change has the potential to affect different regional climates very differently from each other. My intersite research indicated that each region did not capture a ubiquitous global climate pressure. Instead, each region experienced asynchronous climate changes through time. This research is an important first step and a valuable approach in discerning climate change responses among different regions that could, subsequently, be applied more broadly across other regions and lead to improved climate change analyses.
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<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>α</td>
<td>Cronbach’s index of internal consistency</td>
</tr>
<tr>
<td>AD</td>
<td><em>Anno Domini</em></td>
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<tr>
<td>A₀</td>
<td>Surface area of a lake</td>
</tr>
<tr>
<td>ANC</td>
<td>Acid neutralization capacity</td>
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<tr>
<td>AR</td>
<td>Autoregressive function</td>
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<tr>
<td>ARIMA</td>
<td>Autoregressive, integrated moving average</td>
</tr>
<tr>
<td>¹⁴C</td>
<td>Heavy radio-nucleotide of carbon with eight neutrons</td>
</tr>
<tr>
<td>ca.</td>
<td><em>Circa</em>; approximately</td>
</tr>
<tr>
<td>cf.</td>
<td><em>Confer</em>; compare or consult</td>
</tr>
<tr>
<td>cm</td>
<td>Centimeters</td>
</tr>
<tr>
<td>e.g.</td>
<td><em>Exempli gratia</em>; for example</td>
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<tr>
<td>ENSO</td>
<td>El Niño-Southern Oscillation</td>
</tr>
<tr>
<td>g</td>
<td>Grams</td>
</tr>
<tr>
<td>h</td>
<td>SiZer bandwidth</td>
</tr>
<tr>
<td>H₂O₂</td>
<td>Hydrogen peroxide</td>
</tr>
<tr>
<td>HCl</td>
<td>Hydrochloric acid</td>
</tr>
<tr>
<td>ha</td>
<td>Hectares</td>
</tr>
<tr>
<td>ibid</td>
<td><em>Ibidem</em>; the same place</td>
</tr>
<tr>
<td>i.e.</td>
<td><em>Id est</em>; that is</td>
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km Kilometers

L Liters

$log_{10}(h)$ Base-10 logarithm of the height of the wavelength

LOI Loss on ignition

MA Moving average function

mg Milligrams

mm Millimeters

p Probability associated with the occurrence under the null hypothesis of a value as extreme or more extreme than the observed value

$P$ Probability associated with the occurrence under the null hypothesis of a value as extreme or more extreme than the observed value (the capitol $P$ denotes specific reference to the ARIMA model)

PC Principal component

PCA Principal components analysis

permil Parts per thousand

pH Cologarithm of the activity of dissolved hydrogen ions

r Correlation coefficient

SiZer Significance of the zero crossings of the derivative

$T$ Computed value of $t$-test (the capitol $T$ denotes specific reference to the ARIMA model)

USA United States of America

X Multiplied by
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>YBP</td>
<td>Years before present</td>
</tr>
<tr>
<td>$Z_m$</td>
<td>Maximum depth of a lake</td>
</tr>
<tr>
<td>°C</td>
<td>Degrees Celsius (also denoted as “° C”)</td>
</tr>
<tr>
<td>°N</td>
<td>Degrees north latitude (also denoted as “N °”)</td>
</tr>
<tr>
<td>°W</td>
<td>Degrees west longitude (also denoted as “W °”)</td>
</tr>
<tr>
<td>&gt;</td>
<td>Greater than</td>
</tr>
<tr>
<td>&lt;</td>
<td>Less than</td>
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<tr>
<td>+</td>
<td>Plus</td>
</tr>
<tr>
<td>-</td>
<td>Minus</td>
</tr>
<tr>
<td>±</td>
<td>Plus or minus (within a range)</td>
</tr>
<tr>
<td>≈</td>
<td>Approximately equal to</td>
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<tr>
<td>=</td>
<td>Equal to</td>
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<tr>
<td>%</td>
<td>Percent</td>
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ACKNOWLEDGEMENTS

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INTRODUCTION

Comparing only two ecosystems can tell us if the ecosystems are different, but can tell us nothing about why they are different. This is because in doing interecosystem comparisons, our replicate samples must be “ecosystems,” not replicate samples taken within each ecosystem... A real test of the hypothesis that ecosystems differing in X also differ in Y would take a minimum of three ecosystems...


Extensive scientific efforts are currently underway to explore the magnitude and general effects of climate change at global and hemispheric scales (Mann et al. 1995, 1998, Mann and Jones 2003). Despite the availability of many climate change detection methods, considerably less is known about comparative differences in magnitude and extent of climate change on smaller scales that are necessary to improve global forecasting models. This dissertation is an exploration that uses paleo-limnology as an approach to compare cross-regional differences in climate change within sub-arctic, semi-arid, and sub-tropical regions. My central research question is:

To what extent has historical climate change been expressed in three different geographical regions with distinctively different modern climate: sub-arctic Alaska, semi-arid New Mexico, and sub-tropical Alabama?

My research differs from previous climate change and paleo-limnological studies in that I used a design that incorporated, a priori, an approach in which climate responses in different regions
were investigated simultaneously using a uniform proxy method derived from lake sediments. The study sites included lakes in key geographic regions from a climate-change perspective, including under-studied ones in sub-tropical and south temperate climates. I used traditional climate change proxies derived from lake sediment core analyses to identify and interpret climate changes in each region. My fundamental premise is that this research design will allow me to identify and understand climate response differences among regions and, thereby, reduce noticeable gaps in the paleo-climate record of North America.

**Background context**

Rapid climate change during the industrial era demonstrates the critical need to investigate mechanisms forcing these climate anomalies. For example, the AD 1990s were the warmest decade ever recorded since global recordkeeping began in AD 1880 (EPA 1998a, 1998b, NCDC 2006). Furthermore, AD 2005 and 2006 had the warmest yearly average global temperatures ever recorded (NCDC 2006). At smaller scales, the northern hemisphere has warmed 1.5° C since AD 1850, and the upper atmosphere above Antarctica has warmed by 1.5-2.1° C since 1971 (Mann et al. 1998, Mann and Jones 2003, Turner et al. 2006). These data suggest that the planet’s climate has changed 10-100 times faster in the last 150 years than it did during the previous 10,000 years (Miller 1996). This rapid rate of change is forecast to continue with additional warming of 1.5-5.5° C beyond present conditions by the year AD 2100 if inputs of anthropogenic greenhouse gases continue to increase at the current rate from AD 1850 to present (Schlesinger and Mitchell 1987, Overpeck et al. 1997, Mann and Jones 2003). However, there is uncertainty in both the abnormality of the current warming trend and in the confidence of the forecasting models (Brumfiel 2006).
Our understanding of climate change and our ability to model change are quickly growing and changing science from a variety of perspectives. A multitude of climate change detection techniques has yielded many hypotheses and interpretations about forcing mechanisms (Crowley and North 1991, Barry and Chorley 1999). Much is known about long-term climate periodicity caused by Milankovitch cycles (e.g. Henderson-Sellers and McGuffie 1987), but there is uncertainty about the causes of shorter-term global climate changes. Specifically, additional information is critically needed to discern the influence of solar intensity and atmospheric perturbations (e.g. greenhouse gases and aerosols) on the planet’s temperatures. For instance, both paleo-climate and instrument-measured evidence have demonstrated several climate oscillations caused by volcanic activity, including the opposing forces of greenhouse gases (warming) and reflective aerosols (cooling) (Mann et al. 1995, Mann et al. 1998, Moberg et al. 2005). Nevertheless, the increasing levels of anthropogenic greenhouse gases from burning fossil fuels are still hypothesized to be the dominant post-industrialization forcing mechanism driving the current climate change (Overpeck et al. 1997, Mann et al. 1998, Crowley 2000). For example, levels of CO₂ have increased by nearly 100 ppm (40%) over the last 140 years in tandem with increasing global temperatures (Barry and Chorley 1999). Furthermore, the observed tropospheric warming coupled with stratospheric cooling provides additional support for hypotheses of anthropogenic greenhouse gas forcing; the simultaneous warming and cooling balances the first law of thermodynamics with respect to the solar constant (Fu et al. 2004).

However, there are several obstacles limiting our ability to demonstrate undeniably that industrialization has caused climate change. For instance, while evidence linking anthropogenic greenhouse gases and perceived climate changes continues to accumulate, so have questions concerning the potential abnormality of this trend (Brumfiel 2006). Questions arise mainly
because of the stark lack of long-term instrument records pre-dating industrialization from which to compare recent trends. In other words, there is little doubt that greenhouse gases warm the planet, but drawing conclusions about anthropogenic climate change based only on post-industrialization instrument records is incorrect deductive logic. Furthermore, climate change alters the overall average global climate, but this average is often the dampened sum of extreme changes at smaller scales (Barry and Chorley 1999). The complexities of coupled ocean-atmosphere interactions and continental effects have caused severe warming in some regions, little to no warming in other regions, and high variation in precipitation patterns (Crowley and North 1991, Barry and Chorley 1999, Jones et al. 2001). Such variation in regional climates makes it increasingly difficult to evaluate and model the abnormality of any post-industrialization, anthropogenic climate changes (Crowley 2000, von Storch et al. 2004).

Therefore, long-term proxy records from many sources and regions of the world are required to decipher whether recent climate changes that are occurring in coincidence with accumulating greenhouse gases are anomalous or not (Smol 1988, Fritz 1996, Cohen 2003). Such long-term proxy records, encompassing both pre- and post-industrialization time, provide robust methods using well-known climate signals stored in proxies that can validate the perception of abnormal anthropogenic climate change derived from instrument documentation. In most cases, atypical climate trends are identifiable from long-term records because non-anthropogenic climate changes usually follow known cyclical intervals, whereas anthropogenically caused changes would not (Barry and Chorley 1999).

Despite the need for long-term data relevant to climate change, data acquired from instrument records are rare prior to AD 1880, which limits our ability to test the hypothesis that industrialization caused climate change. Thus, researchers must rely on proxy data that represent
climate changes over long-term time series (Cohen 2003). The United States National Academy of Sciences (NAS) recently endorsed some long-term proxy data that suggested the 1990s were the warmest years in the last millennium (Brumfiel 2006). Yet, the NAS report also cautioned, due to both proxy uncertainty and sporadic sample site locations, that more records from additional regions are needed for comparing the extent of recent climate change over space and time. Also, region-specific replication using a variety of different proxy methods is needed to validate current findings (Mann 2002). Additional site records are needed to fill in gaps in the global models, thereby reducing both random and systematic errors in the climate forecasts.

Therefore, the next exciting challenge for paleo-climate research is to evaluate and validate the variation in regional climate changes over broad spatial scales.

However, difficulties arise in identifying appropriately similar proxies that are useful across broad geographical regions. A variety of paleo-climate proxies have been used with confidence for regional climate reconstruction, including tree rings, ice cores, and marine carbonates (Crowley and North 1991, Cohen 2003). While these techniques are robust, they are often not amenable to cross-regional comparisons because trees, icecaps, and marine carbonates are not intermixed, ubiquitous regional features across many environments. For example, icecaps are usually limited to the upper latitudes, and trees are typically absent in the upper latitudes. Furthermore, even though marine carbonates are perhaps the most robust paleo-thermometer (Faure 1986), their application is severely limited when assessing inland continental temperatures.

Therefore, the principal task for designing cross-regional paleo-climate research is identifying appropriately similar methods and uniform proxies that are encompassed within a wide variety of landscapes. My chosen paleo-climate method, diatom paleo-limnology, is a
highly useful technique for regional climate reconstructions (Battarbee 1986, Cohen 2003). Lakes are well-known integrators of landscape features, evolution, and temperature (Wetzel 2001, Cohen 2003). They are also abundant worldwide, contain an array of ubiquitous, long-term proxy types stored in benthic sediments, and the rapid collection of large suites of information worldwide is relatively cost effective. Moreover, lake proxies have been demonstrated to be robust archives of climate change proxies (Cohen 2003).

My research reported here addresses the critical need for multi-regional, paleo-climate research. Specifically, I used diatom paleo-limnology to compare the extent of climate change in three different climate zones: the sub-arctic (Alaska), the semi-arid (New Mexico), and the sub-tropical (Alabama). Each of these regions currently shows contrasting responses to climate change: warming has been rapid in the arctic and sub-arctic, warming has been minimal in the tropics and sub-tropics, and precipitation has been reduced, while temperatures have increased, in inland arid and semi-arid environments (Crowley and North 1991, Cox et al. 2000, Whitfield 2003, Westerling et al. 2006). These three climates provide stark contrast within a single continent and offer ideal settings to evaluate variation in regional climate changes. However, the majority of paleo-limnology studies worldwide have come from glacial lakes in north temperate regions and the great rift lakes of Africa and Asia (Cohen 2003). In addition, when sediment core data are cross-regionally compared, it is often a post hoc synthesis from different, independent studies with a non-uniform collection of different proxies of varying sensitivity (cf. Crowley and Lowery 2000). This approach likely limits interpretation of cross-regional climate responses.

My use of diatom paleo-limnology to study climate change is the first to compare, a priori, a range of regions using a uniform proxy method capable of elucidating decadal-scale
climate change. Also, I statistically validated my diatom-inferred records of climate change in Alaska and New Mexico with independently derived paleo-climate proxies, and I confirmed my diatom-inferred findings in Alabama with other diatom records from the southeastern United States. To this end, my research provided needed regional replicate data that will further reduce gaps in the paleo-limnology and paleo-climatology records. Moreover, it is a demonstration that the diatom approach can be validated from independently derived proxies; this combination of using a validated, uniform proxy method across multiple regions is a powerful technique that can advance paleo-climate research.

Value of inter-regional ecosystem research

Large-scale, comparative inter-site/inter-regional ecosystem research is an emerging science of paramount importance (Downing 1991). Previously, inter-site comparisons have validated ecological theories by experimentally testing aspects of ecosystem structure and function (e.g. Likens et al. 1970, Schindler 1974, Carpenter and Kitchell 1993, Carpenter et al. 1998). Currently, inter-site research is rapidly gaining interest and being expanded to address larger-scale biotic responses and interactions of ecosystems, climate, and land use (NEON 2006). Inter-regional research provides the ability to test ecosystem-level theories and generates data that are urgently needed by decision makers as negative anthropogenic effects increasingly encroach on many ecosystems. With respect to climate change, inter-regional research is critical to understanding the relationship between anthropogenic effects and atmospheric alterations because climate change affects different regions in diverse ways. My cross-regional paleo-limnology approach to climate change is an important first step in providing inter-regional,
comparative proxy data of equal sensitivities that will certainly improve climate change forecasts.

Site selection rationale

I selected the three states of Alaska, New Mexico, and Alabama as my regional representatives because of their different climate and geographic features:

- **Alaska**: sub-arctic; rapid warming and melting glaciers (albedo effects).
- **New Mexico**: semi-arid; extreme droughts projected (continental interior warming effects).
- **Alabama**: sub-tropical and humid; coastal (oceanic effects).

Research assumptions

My research assumes climate change is detectable by examination and classification of diatom frustules. Diatoms have a thoroughly documented history as proxies of climate change (Battarbee 1986, Fritz 1996, Cohen 2003). Specifically, diatoms are highly effective as climate surrogates when the following assumptions are valid:

- Atmospheric temperature controls lake temperature; changes in lake temperature represent changes in atmospheric temperature.
- Atmospheric precipitation affects lake level and lakewater chemistry; changes in lake level and/or chemistry represent changes in precipitation.
- Species-specific diatom profiles change in response to changes in lakewater temperature, level, and chemistry.

**Approach**

I hypothesized that historical climate changes altered diatom communities and sedimentation throughout the cores in each of my study lakes. Furthermore, from these alterations, it would be possible to identify possible causes forcing these changes in each individual lake. To resolve my hypotheses, my approach had two central aspects.

First, following the guidelines of Downing (1991), I selected three study sites and a low number (2) of dependent variables (sedimentation data and diatom species assemblages). Each variable type presumably has equal sensitivity to environmental processes across regions, which makes intersite comparisons more amenable. Within each site, I used the same methods to quantify diatom responses and sedimentation. This design should distinguish whether each region is similar or different from each other with respect to climate change forcing mechanisms. More importantly, it should tell me why they are dissimilar because diatoms differentially respond to climate stimuli, such as temperature and precipitation (Battarbee 1986, Fritz 1996).

Second, I required the use of statistical analyses on my dependent variables within each lake. Traditionally, paleo-limnology studies have not used statistics to quantify changes through time. Instead, they have relied upon visual comparisons of graphical data. Paleo-limnology is a robust ecosystem science because of its ability to collect long-term time series data. However, long-term ecosystem data often have significant amounts of covariance and noise (Gotelli and Ellison 2004, von Storch et al. 2004). These aspects can dampen significant trends and/or create the illusion of changes when no change is statistically present. Therefore, in order to investigate
similarities and differences between diatoms from each study region robustly, it is necessary to account for noise and covariance in the data to identify true trends within each lake. This is paramount especially because diatoms are often cosmopolitan with rapid dispersal; it is necessary to calculate statistically whether a population increase or decline is a random, noisy phenomenon or if it was linked to some environmental process. I chose a combination of statistical treatments that should minimize noise in the data analyses and improve the identification of significant changes in the variables from each lake. By visually comparing significant data trends (apices, nadirs, and bifurcation points) from within each lake, it may be possible to identify any differences in the dominant climate forcing mechanism between each of my study sites. Then, the inferred dominant forcing mechanism from each lake could be compared to the literature and statistically validated from existing climate data. This is important because climate change is expected to affect different geographical areas in varying manners, which may include non-temperature changes.

Organization

In order to better understand regional differences in climate change between sub-arctic, semi-arid, and sub-tropical climates, I investigated changes in representative diatom communities and sedimentation through time from three lakes. The results from this investigation are divided into three chapters as an article-style dissertation. Chapter 1 explored diatom changes in sub-arctic Alaska and statistically validated changes with an independent paleo-thermometer. In my next article in Chapter 2, I investigated diatom responses in semi-arid New Mexico and validated them with independently derived metrics of precipitation and solar intensity. My last article, Chapter 3, assessed diatom community changes and sedimentary
characteristics in Alabama and compared them to other diatom-inferred climate records in the southeast USA. Finally, I close the dissertation with an overall conclusions chapter that highlights the utility of diatoms as climate proxies in diverse environments.
CHAPTER ONE: A VALIDATED DIATOM-INFERRED RECORD OF REGIONAL TEMPERATURE CHANGE OVER THE LAST FOUR MILLENNIA FROM AN ALASKAN LAKE, USA

Abstract. I investigated mid-to-late Holocene (4300 YBP to present day) climate change in mainland, sub-arctic Alaska, USA, using diatom frustules sampled from a lake sediment core. Diatom data were analyzed using a combination of multivariate ordination, time series analysis, and time series modeling to identify points of significant transition through time. Species and genera profiles were used to identify statistically significant periods of transition between warming apices and cooling nadirs. The diatom-inferred climate in the region was cyclical, with five periods of cooling and six periods of warming between ≈ 4300 YBP and present day. Diatoms significantly changed to colder water assemblages between ≈ 4100-3825 YBP, ≈ 3535-3350 YBP, ≈ 2670-1660 YBP, ≈ 1570-955 YBP, and ≈ 300-170 YBP. Conversely, diatoms shifted to warmer water assemblages between ≈ 3825-3535 YBP, ≈ 3350-2670 YBP, ≈ 1660-1570 YBP, ≈ 955-300 YBP, and from ≈ 170 YBP to present. These diatom-inferred climate changes are in general agreement with global climate change records and also have strong statistical concordance with an independently derived paleo-thermometer constructed for the region. Also, significant warming was inferred within the most recently deposited sediments (< 170 YBP) and was also forecast-modeled to continue into the future. However, the magnitude of this recent change within the diatom communities was no more drastic than other periods of inferred warming in the sediment core. These results suggest the sub-arctic has warmed concurrently with global warming predictions, but the warming was not as unprecedented as
warming in the high arctic. The methods and results presented here are of value in advancing diatom analyses of climate change, particularly in regions at or near environmental thresholds.

**INTRODUCTION**

*Study background*

Predicting patterns among organisms and their environment is among the core tenets of ecology. Indeed, never has the need for deciphering these relationships been as important as it is now, because anthropogenic alterations will further impact global temperatures, ecosystem services, and human well-being (Clark et al. 2001, Scheffer et al. 2001, MA [Millennium Ecosystem Assessment] 2005). While there is no longer much debate over the reality of anthropogenic climate warming, a robust understanding of natural, baseline climatic variability over the long term is paramount to incorporate accurately confounding human perturbations into potential climate change forecasts (Crowley and North 1991, Jones et al. 1998, Crowley 2000). However, despite this need for long-term data relevant to climate change, data acquired from thermometers are rare prior to AD 1880 (129 YBP), which limits our ability to integrate fully anthropogenic impacts with respect to baseline conditions. Thus, researchers must rely on paleo-proxy data, both geochemical and biological, that represent temperature changes over long-term time series (Cohen 2003). By analyzing many series of historical ecological patterns within the paleo-proxy archives, it is then possible to estimate the approximate date of origin of anthropogenic impacts, as well as the current magnitude of these impacts, and also to model projections of any continued anthropogenic impacts on the global climate system (Mann et al. 1995, 1998). In most cases, atypical warming trends can be identified from long-term records
because non-anthropogenic climate changes usually follow known cyclical intervals, whereas anthropogenically caused changes would not (Barry and Chorley 1999).

Arctic and sub-arctic regions, despite the brevity of their thermometer records (< 75 YBP [Hu et al. 2001]), are model ecosystems for studying climate change phenomena for at least two reasons (Smol et al. 2005). First, coupled cryospheric feedback processes of ice cover and albedo can greatly accelerate both warming and cooling events when compared to concomitant climate changes at lower latitudes; this relationship provides strong predictive power within general circulation models of climate change and also causes paleo-climate proxy signals to be very pronounced (Chapman and Walsh 1993, Barry and Chorley 1999, Cox et al. 2000, Cohen 2003, Rawlins and Willmott 2003). Second, lakes are robust paleo-climate archive repositories (Fritz 1996, Cohen 2003) and are highly responsive to climate change, particularly in the arctic latitudes (Smol et al. 2005, Smol and Douglas 2007). Specifically, small changes in atmospheric temperatures can greatly alter ice cover regimes and, ultimately, growing season durations (Wetzel 2001). These linked mechanisms have cascading effects that often change the structure of diatom (Bacillariophyta) communities; as such, diatoms are considered to be one of the most important biological paleo-temperature proxies in lacustrine environments (Battarbee 1986, Fritz 1996, Cohen 2003, Smol et al. 2005, Smol and Douglas 2007).

A large knowledge base exists within the literature demonstrating the utility of diatoms deposited in lake sediments as indicators of past environmental conditions (Battarbee 1986, Fritz 1996, Cohen 2003, Podritske and Gajewski 2007). Burgeoning studies within the last two decades from high latitude Canadian and Greenland lakes have focused on improving the utility of diatoms as surrogates of temperature change over varying time durations throughout the Holocene. The working hypotheses of Smol (1983, 1988) about rapid changes within arctic
diatom communities in response to recent warming conditions established a specific, testable paradigm describing diatoms as arctic climate surrogates. Smol (1983, 1988) hypothesized that diatoms respond to habitat availability, and habitat availability is closely linked to climate. These hypotheses are based on the assumptions that arctic lakes are highly responsive to small temperature changes. A few degrees of warming can greatly alter ice cover and growing seasons, which leads to higher overall productivity and community compositional changes as new habitats and nutrients become available for longer periods throughout the year (cf. Rouse et al. 1997, Smol et al. 2005, Smol and Douglas 2007). During cold periods with extensive ice cover, benthic species will dominate because open water on the lake is short-lived and, when it is present, is most often found around the border of the lake in the shallow littoral zone. During warm periods, larger areas of open water in the lake persist longer than during cold periods, which causes enhanced thermal stratification and more wind-induced turbulence. These conditions favor planktonic diatoms because they are suited to take advantage and remain suspended in this newly available habitat of open water. Consequently, because the response time of diatom communities is very rapid, diatoms are extremely useful and reliable indicators of temperature changes because there is little to no problem with lag effects (Smol 1988).

The hypotheses of Smol (1983, 1988) were followed by the robust, high-resolution diatom analyses of Douglas et al. (1994), Pienitz et al. (1995), Gajewski et al. (1997), Joynt and Wolfe (2001), Rühland et al. (2003), Rühland and Smol (2005), Antoniades and Douglas (2005), and Podritske and Gajewski (2007), which together resolved a generalized framework for using recent (< 150 YBP) and stark changes in diatom communities as reliable indicators of rapid warming and environmental change in the arctic latitudes. The major conclusions from these arctic studies, focusing on recently layered sediments, found that long-existing, stable
communities of benthic diatoms were indeed being rapidly replaced by planktonic species in the
most recently deposited sediments during periods of rapid (< 100 years), concomitant warming.

Furthermore, the synthetic meta-analyses of Smol et al. (2005) and Smol and Douglas
(2007) have compared many recent and rapidly changing diatom community structures across
the circumpolar arctic (42 diatom stratigraphies) to known thermometer temperature increases
over the last two centuries. These meta-analyses created a high-resolution suite of potential,
expected diatom species and genera profiles that were calibrated to varying environmental
conditions for each lake (Table 1). The empirical data from the 42 diatom stratigraphies (Smol
et al. 2005, Smol and Douglas 2007) support the initial diatom hypotheses (Smol 1983, 1988)
and validate the diatom approach of using newly layered sediments to assess recent arctic
warming. Only those lakes that were in regions experiencing warming in recent decades
demonstrated generic shifts in diatom composition (consistent with Table 1). Conversely, those
sites with no warming demonstrated no changes in diatoms. The shift from benthic diatoms to
planktonic diatoms was concomitant with thermometer-recorded warming.

While every lake will have varying calibrated paleo-limnological trajectories (Smol and
Douglas 2007), it may be possible to use these generalized suites of predictions to test warming
hypotheses in a variety of other lakes across the arctic and sub-arctic. The work of Saros et al.
(2003) demonstrated that these predictions could be generally supported in sub-arctic regions
from the analysis of a 400-year record from a lake in the alpine, temperate United States.
Furthermore, the more recent synthesis (> 200 diatom stratigraphies) of Rühland et al. (2008)
demonstrated that changes in the trends of Aulacoseira spp., Cyclotella spp., and Fragilaria
sensu lato could be applied throughout the upper latitudes of the northern hemisphere as reliable
surrogates of recent, rapid warming. With global temperatures predicted to increase imminently,

<table>
<thead>
<tr>
<th>Temperatures</th>
<th>Diatom community characteristics</th>
<th>Potential suite of predicted dominant diatom genera</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colder¹</td>
<td>Abundance of benthic and aerophilic species</td>
<td>Aulacoseira spp., Fragilaria sensu lato (new synonyms: Fragilaria, Pseudostaurosira, Staurosira, and Staurosirella spp.), Pinnularia spp.</td>
</tr>
<tr>
<td>Warmer²</td>
<td>Abundance of planktonic and deep water species</td>
<td>Achnanthes spp., Cyclotella spp., Cymbella spp., and Nitzschia spp.</td>
</tr>
</tbody>
</table>

Notes: ¹Genera that are reported to be typical in colder waters and are reduced in abundance as waters become warmer; ²Genera that are reported to increase their abundance as waters become warmer (Smol et al. 2005, Smol and Douglas 2007)
research from many disciplines is needed to identify the extent and magnitude of warming. The diatom approach to identifying rapid warming in the northern latitudes is emerging as one such reliable method.

**Study objective and hypotheses**

The overall emphasis of my study was to test and extend the applicability of the generalized suite of arctic diatom predictions (Table 1) of Smol (1983, 1988) and the syntheses of Smol et al. (2005), and Smol and Douglas (2007) to sub-arctic regions. Specifically, I explored diatom-inferred temperature changes in sub-arctic Alaska. With this purpose, my approach followed five steps. First, I tested a longer sedimentary record over a longer time period (compared to references ibid) that could potentially include both cooling and warming events. I was interested in testing whether predictive warming responses of diatoms in recent sediments (Smol 1983, 1988, Smol et al. 2005, and Smol and Douglas 2007) could also be applied in reverse to cooling conditions that may be present in longer (references ibid) sedimentary records. Second, I applied novel statistical analyses to the diatom time series to test for any significance in potential changes in the diatom community structure. Third, I validated diatom trends against an independent source of paleo-proxy temperature data. Fourth, I generated a forecasting model based on historical diatom assemblages to create a potential future scenario of any continuing environmental change in my study region. Finally, I realized there was an opportunity to supplement the diatom archives with a study site from Alaska, which is surprisingly underrepresented when compared to other locations (cf. Rühland et al. 2008).

I chose Alaska as a representative site of the sub-arctic United States for two main reasons. First, while the sub-arctic has not experienced alterations in ice cover regimes as
drastically as the high arctic (Rouse et al. 1997), the instrument record indicates that the Alaskan mainland has warmed by 1.5° C since AD 1850 (159 YBP) and 0.6° C since AD 1960 (49 YBP) (Miller 1996, Rawlins and Willmott 2003), which provides an ideal setting to test predictive shifts in diatom communities in a region of known warming over the short-term. Furthermore, the paleo-climate of interior Alaska has been cyclical during the last two millennia with inferred temperature spreads of up to ca. 5° C (Hu et al. 1998, Hu et al. 2001). These cyclical patterns further extend the ability to test the diatom predictions (Table 1) over the long-term encompassing both historical cooling and warming events in the sub-arctic United States.

Based on the diatom predictions summarized in Table 1 and the paleo-temperature work of Hu et al. (2001), I tested two main hypotheses about the diatom communities deposited in my sub-arctic Alaskan study lake:

H1: Temperature fluctuations changed diatom community structure in my study lake. The diatom community would be highly plastic throughout the length of the core (> 4000 years), demonstrating statistically significant genera shifts that align with temperature patterns.

H2: The diatom community in my study lake would show the most statistically drastic shift, when compared to the whole time series, over the most recent 150 years within the core and would also continue to show rapid changes when forecast into the future.


Study importance

This study uses an application of statistical analyses on diatom community changes over time. Traditionally, many diatom paleo-limnology studies have not used statistics to analyze changes in community structure; rather, they have relied upon visual inspection of graphical representation of changes through time. Alternatively, some studies have used metrics of composition based on habitat or body morphology in an attempt to standardize transitional gradients (see Battarbee 1986). I argue that statistics are paramount to diatom paleo-limnology studies. One of the strengths of diatom paleo-limnology studies is the ability to collect data from extremely long time series. However, long-term time series data often have significant amounts of noise, which can mask actual significant trends and/or produce type-1 errors by creating the illusion of drastic shifts when one is statistically not present (Bowerman and O’Connel 1993, Rondonotti et al. 2007). In order to test robustly the diatom predictions outlined in Table 1 over long-term time series, it is critical to account statistically for noise in the data and to identify true data trends. Some multivariate ordinations have been used in recent diatom paleo-limnology studies to reduce the dimensionality of the diatom community, but a need for quantitative null hypothesis testing remains. My approach is the first diatom paleo-limnology analysis to use a newly derived time series analysis (SiZer [Zhang and Marron 2005, Rondonotti et al. 2007]) in order to conclude definitively if changes in diatom communities over time were statistically significant at any given point in time.

Furthermore, my study takes the next incremental step forward in using diatoms as indicators of climate change. The robust research of Smol (1983, 1988), Smol et al. (2005), and Smol and Douglas (2007) has shown, using very detailed and calibrated species and genera accounts, that diatoms are robust indicators of recent warming (< 150 years) in arctic regions.
Many other studies have used diatoms as generic indicators of temperature change over longer periods (thousands of years), but without the systematic specificity of Smol (1983, 1988), Smol et al. (2005), and Smol and Douglas (2007). My study is the first diatom paleo-limnology project that tests hypotheses of climate change over thousands of years using species and genera specific predictions (Smol [1983, 1988], Smol et al. [2005], and Smol and Douglas [2007]) with time series statistical analyses and time series forecasting modeling of the diatom communities. Also, my study is the only one to validate these approaches of diatom-inferred climate changes with an independently derived paleo-thermometer from a lake in close regional proximity (from Hu et al. 2001). The results presented here and, perhaps more importantly, the methods will help to advance the field of diatom paleo-limnology by demonstrating both the utility and effectiveness of time series statistics and modeling of diatoms as climate change proxies. The sum of all advances in diatom paleo-limnology will certainly aid in progressing the critically needed field of anthropogenically induced climate change science.

METHODS

Study site

Jewel Lake (N 61° 49’ 11.8”, W 147° 50’ 7.3”) is a proglacial, sub-arctic lake (surface area = 8.0 ha, maximum depth = 4.5 m, age = 7000-8000 years [see Larson et al. 2003 for a detailed description of the glacial geology of the Matanuska Valley], 587 m above sea level, AD 2005 springtime pH =7.8) located approximately 6 km northwest of the terminus of the Matanuska Glacier and 130 km northeast of Anchorage, Alaska (Fig. 1). The lake is located within the Interior Climate Zone of Alaska, isolated from development, and experiences minimal perturbation; anthropogenic nutrient inputs (non-atmospheric) are likely low or none. The
FIG. 1. Location map of the study site, Jewel Lake, with reference to the Matanuska Glacier and the site of Hu et al. (2001) in Alaska, USA.
current mean annual temperature of the Interior Climate Zone is -3.5°C, with a mean January
temperature of -16.7°C and a mean July temperature of 12.7°C. The mean annual precipitation
is approximately 40 cm, including 127 cm as snow (Hu et al. 2001, Walker 2005).

The region has undergone several transformations since the start of the Holocene.
Previous studies have suggested that a complex interaction of retreating glaciers, temperature
change, and fluctuation in atmospheric moisture and circulation patterns have changed the
vegetation of the region (Hu et al. 1998, Walker 2005, Yu et al. 2008). At approximately 11,000
YBP, the region was dominated by herbaceous tundra with widespread *Populus* and stands of
birch trees (*Betula*). Throughout the Holocene, these were increasingly replaced by alder
(*Alnus*), spruce (*Picea*), and various grasses (Poaceae), which now constitute the majority of the
current vegetation.

*Paleo-temperatures*

To validate my diatom-inferred temperature trends, I used the 2000-year (present day to
2000 YBP) paleo-climate reconstruction of western Alaska provided to me by F.S. Hu (also
reported in Hu et al. 2001) as my independent regional paleo-temperature reference. While
continental, hemispheric, and global temperature reconstructions are highly accurate and useful
(e.g. the global Holocene record of Mayewski et al. [2004]), I specifically wanted a regional
temperature reconstruction that was near my study site. The results of Hu et al. (2001) are from
stable isotope analyses of $^{18}$O ratios derived from inorganic carbonate in the lake sediments. It
was possible to reconstruct inferred lake temperatures because $^{18}$O fraction in inorganic
carbonate is a function of lakewater temperature. The inferred temperatures represent growing
season average water temperature anomalies compared to the present. Furthermore, those results
are corroborated by other studies of global temperature changes (e.g. Lamb 1977, Stine 1994, Broecker 2001) and overall landscape environmental history (Walker 2005). Additionally, their study lake (N 62° 33’, W 153° 38’) has similar sedimentation rates as mine (their lake core sediments integrate as 5 mm of sediment ≈ 22.5 years as inferred from $^{14}$C dating; my lake core integrates 5 mm of sediment ≈ 25 years as inferred from $^{14}$C dating) and is within 306 km of Jewel Lake (Fig. 1).

**Sediment core**

In April AD 2005 I retrieved a continuous 970 mm sediment core from the deepest portion of the lake by using a 6.5 cm wide core barrel attached to a modified Glew gravity corer (Glew 1989). The lake was iced over, and the sediment corer was lowered through a 25 cm wide hole in the ice. Upon retrieval, the core was stored at a constant temperature of 4º C until removed for analyses. Within the laboratory, the core was extruded and sectioned into 194 discrete 5 mm sections. Approximately 1 g wet mass was taken from each 5 mm sub-sample for diatom analyses. The remaining portion of each sub-sample was dried at 50º C until a constant mass was obtained. Once a constant mass was obtained, the sub-samples were finely ground with a mortar and pestle. Approximately 1 g dry mass from each 5 mm sub-sample was combusted at 550º C for 24 hours to determine organic content from loss on ignition (LOI). After combustion, samples were weighed, rehydrated with deionized water (18 megohm-cm resistivity), dried, and weighed again to account for any loss of water of hydration.

Additionally, 11 uncombusted sub-samples in the sedimentary sequence were sent to the National Ocean Sciences Accelerator Mass Spectrometry Facility, Woods Hole, Massachusetts for reservoir-corrected (present day = AD 1950; calibration data from INTCAL 98 [Stuvier et al.
1998]) $^{14}$C dating of bulk organic matter taken from the depths of 0 mm (top of core), 21 mm, 71 mm, 231 mm, 331 mm, 406 mm, 431 mm, 621 mm, 711 mm, 746 mm, and 961 mm. These depths were chosen because they were either at approximately evenly spaced intervals or they were potential transitional horizons as inferred from color and/or compositional changes. The age-depth profile was fitted with cubic spline regression. Because of the extrapolation of estimated dates between each known $^{14}$C date, all extrapolated dates will be noted with the symbol “$\approx$” throughout the text. The bottom of the core dated to $\approx 4298$ YBP ± 40 years. Each 5 mm sample averages $\approx 25$ years of sedimentation (top-most samples $\approx 12$ years; bottom-most samples $\approx 30$ years).

**Diatom enumeration**

I digested the ca. 1 g wet mass of lake sediments from each 5 mm sub-sample designated for diatom analyses following the guidelines of Battarbee (1986). Wet samples were first washed with 10% HCl and rinsed with deionized water (18 megohm-cm resistivity) to remove any carbonates. Then, the samples were digested with 30% H$_2$O$_2$ to remove organic matter and given a final rinse with deionized water. At this point, only silicates remained suspended in deionized water. To avoid damaging any frustules, all suspended samples were allowed to settle via gravity for 24 hours after each washing and rinsing sequence in lieu of centrifuging. No sieving was necessary because the sediments were devoid of coarse-grained (> 0.5 mm) organic and inorganic debris. Occasionally, mollusk shells were present before HCl washing, and they were removed by forceps. Also, separation of diatoms via suspension in heavy liquids was not necessary. Finally, washed samples were allowed to evaporate on glass cover slips before permanently mounted on glass slides with Naphrax (refractive index = 1.65).
Diatom species were identified by use of 1000X phase-contrast microscopy with a Zeiss Axioskop microscope following the taxonomy of Patrick and Reimer (1966, 1975), Foged (1981), and Wehr and Sheath (2003). Recent taxonomic advances have split many taxa of the former genus *Fragilaria sensu lato* into several new genera, including *Fragilaria*, *Pseudostaurosira*, *Staurosira*, and *Staurosirella* spp. (Williams and Round 1987). All species taxonomy and names were updated and verified with the Integrated Taxonomic Information System database (ITIS) and the North American Diatom Ecological database with information current as of July 2008. When possible, at least 300 frustules per 5 mm sample were counted to determine the relative abundance of each species. When it was not possible to enumerate 300 frustules per sample due to diatom paucity, four slide transects encompassing 50 fields of view were counted. Also, broken frustules were ignored unless the broken valves had enough material (usually > 50% of the valve remaining) to allow proper species identification with the dichotomous key. In total, 55,872 frustules from a total of 82 species from 36 genera were identified and enumerated.

**Statistical analyses**

I analyzed the diatom relative abundance data in three steps. For the first step, the relative abundance matrix was normalized using the arcsine-square root transformation (Gotelli and Ellison 2004). Second, to reduce the dimensionality of the diatom community, I performed principal components analysis (PCA) on the variance-covariance matrix of the normalized diatom relative abundance data over the 194 sub-samples. PCA is appropriate for the multicollinearity often found in time series and relative abundance data (Gotelli and Ellison 2004). I used the variance-covariance matrix because it preserves random noise in the variables,
it preserves the sums of the variances, and PCA assumes that large variances in the matrix have large dynamics in PCA space. All of these aspects are important when identifying data noise and true trends, especially within newly created multivariate PCA variables (Johnson 1998). Each principal component (PC) point along a PCA axis is a factored representation of the entire diatom community at that specific point. The major species loadings on each PCA axis indicate the ecological characteristics of the community at each step. Third, I analyzed the newly created PCA axes with SiZer (significance of the zero crossings of the derivative). SiZer is a statistical technique that applies a series of smoothing functions based on bandwidths around the data to statistically analyze which data in a matrix or series are true trends and which data are noise or are attributable to sampling variation (Zhang and Marron 2005, Rondonotti et al. 2007). Essentially, SiZer identifies the true modality of the data by applying derivatives; where there is a significant zero crossing of the derivative ($\alpha = 0.05$ around confidence interval 0), there is a significant shift in the composition of the data structure that is independent of noise or sampling variability. SiZer is a freeware application that is distributed from www.wagner.com.

I also applied SiZer to other data analyzed in my study, including the paleo-temperature data of Hu et al. (2001), the percent organic matter in the sediments determined from LOI, and the relative abundances of species of diatoms with the strongest PCA loadings. All analyses were performed at $\alpha = 0.05$. While all statistical analyses, including SiZer, were applied to the entire data series of 194 samples (one every 5 mm), I omitted sample depths 545-700 mm (samples 110-140) for visual purposes in all subsequent figures because the sediments in this range were mainly glacial flour, had an inverted $^{14}$C date, and < 10 diatoms per sub-sample.

As a more rigorous test of correspondence, I also used cross-correlation analysis to analyze overlapping patterns in diatom PC1 and the paleo-temperature data from Hu et al.
Before applying cross-correlation, I deleted any diatom PC1 point that had no corresponding paleo-temperature with a carbon date within ± 5 years of it. I also deleted all diatom PC1 points between 4300-2000 YBP to align them with the paleo-temperature data. Cross-correlations was run at a 0-100 year lag at $\alpha = 0.05$.

**Time series forecast**

I used an autoregressive, integrated moving average (ARIMA) model (Bowerman and O’Connell 1993) to time-series model the PCA axis 1 data with the goal of generating a forecasted diatom PC1 assemblage beyond present day. If Jewel Lake has been on a warming trajectory, then the model would be able to forecast changes in diatom PC1, which could be interpreted as proxies of expected warming. The model was self-calibrated by using all 194 PC points along the axis and was used for forecast 20 steps into the future (each step = 12 years based on most recent sedimentation rates; 20 steps = 240 years) based on the trend analyses of the previous 194 points. Unlike regression analysis, ARIMA is able to forecast cyclical, curvilinear data with high precision and accuracy as long as the founding principles are robust (Bowerman and O’Connell 1993). To generate the most unbiased model (most conservative in forecasting), I removed the series mean, linear trend, and seasonality from consideration while calculating the forecast. ARIMA models are useful data analysis techniques because, in addition to generating forecasts, the final trajectory of the forecast itself can provide considerable insight about the most recent data in the existing time series.
RESULTS

Paleo-temperatures

The paleo-temperature data from Hu et al. (2001) are presented in Fig. 2 and show considerable variation through time. Over the course of the last two millennia, temperatures in western Alaska fluctuated by up to ca. 5°C. Compared to present day, there were warming peaks of about 2°C at 1900 YBP and 1800 YBP, respectively. After these warming peaks, there was an extensive cooling period, with a nadir of about 3.5°C at 1400 YBP, between 1800-1200 YBP. Following this cooling period, there were brief warming points between 1000-800 YBP. Furthermore, signals of the Little Ice Age (up to 2°C cooler by 200 YBP) were also present. Moreover, the 20th century had the warmest temperatures in Alaska over the last 1000 years.

My SiZer analyses of the data from Hu et al. (2001) indicated that these temperature trends were significant transitions along the continuum between the family of bandwidths in the log_{10}(h) = 2.15 to 2.38 spectra (Fig. 2). A significant cooling trend originated at 1650 YBP, which ended at the beginning of the Medieval Warm Period that spanned 945-680 YBP, which was also a significant temperature shift. After this warm period, another significant cooling trend (portions of the Little Ice Age) began and lasted until 150 YBP. At this point, a warming trend began; this warming trend continued to the end of the data series, which is consistent with most data of warming in the arctic and sub-arctic (cf. Rawlins and Willmott 2003).

Sediment core characteristics

The chronosequence of the Jewel Lake core was established from 11 ^{14}C analyses. Each carbon date was the median calibrated age using a 2-sigma calibrated age range (INTCAL 98, Stuvier et al. 1998). The dating sequence was in chronological order with the exception of
FIG. 2. Inferred paleo-temperatures of western Alaska generated by Hu et al. (2001). The temperature data were redrawn with permission from data sent directly from F.S. Hu. Data represent growing season deviations in water temperatures when compared to present day. The line with small, opaque circles is the original data of Hu et al. (2001). The dashed line is the linear regression of temperatures, which is an important component in calculating zero crossings of the derivative. The other solid lines are the SiZer family of bandwidths in the log_{10}(h) = 2.15 to 2.38 spectra. The open circles indicate points of significant change based on zero crossings of the derivative.
sediment depths 545-700 mm (discussed below). The top sample of the core was $^{14}$C dated as post-present day (present day = AD 1950; 0 YBP ± 50 years) and, thus, was considered as AD 1950 (0 YBP) to maintain consistency with the other 10 $^{14}$C dates. The bottom of the core dated to 4298 YBP ± 40 years. The sedimentation rate of Jewel Lake was relatively constant, ranging between 0.42 mm per year (5 mm = 12 years) at the top of the core to 0.17 mm per year (5 mm = 30 years) at the bottom. An age-depth profile of sediment, $^{14}$C age, and $^{14}$C errors are presented in Fig. 3. Each age-depth profile point along the continuum was estimated from a cubic spline regression of the accepted 10 $^{14}$C dates (discussed below).

The Jewel Lake core was dominated by a nearly homogenous mixture of marl and gyttja at all depths from the surface to the bottom. However, samples between depths 545-700 mm were nearly devoid of marl and gyttja and were instead dominated by glacial flour. The glacial flour was primarily composed of the major bedrock constituents formed by the Cretaceous Matanuska Formation (Walker 2005, Yu et al. 2008). The formation includes a variety of marine shales, volcanic-lithic siltstone, sandstone, and conglomerates (Walker 2005, Yu et al. 2008). It is likely that an ice or moraine dam was breached, resulting in flooding of the lake that deposited 165 mm of glacial flour in a short period (see Larson et al. 2003 for more information about glacial history in the region). The $^{14}$C chronosequence is nearly continuous and uninterrupted between sediment layers bordering the bottom of the flour layer (≈ 2700 YPB) to the top of the flour layer (≈ 2625 YBP); however, a $^{14}$C date taken within the glacial flour was slightly younger (depth = 621 mm, age = 2340 YBP ± 50 years) than both the surrounding top and bottom layers, which is most likely the result of sedimentary mixing as the flour entered the lake or from experimental errors caused by having a low organic content (< 5% LOI) within the flour.
FIG. 3. Age-depth profile for the Jewel Lake sediment core based on $^{14}$C analyses. The points were best-fit with a cubic spline regression. Error bars are age errors generated from the fraction of modern $^{14}$C errors.
available for $^{14}$C dating. Consequently, this $^{14}$C date was disregarded when constructing the age-depth profile.

The bulk organic content of the core was generally low and highly variable throughout the core (Fig. 4), ranging from a low of 5.7% (LOI) to a high of 16.9% (LOI) when excluding the sedimentary layers between 545-700 mm that were mainly glacial flour (< 5% LOI). SiZer indicated five significant transitions in the organic matter content between the family of bandwidths in the $\log_{10}(h) = 1.79$ to 2.36 spectra (Fig. 4). At $\approx 2798$ YBP the organic content transitioned to a significantly lower proportion than the previous running trend. Conversely, at $\approx 1976$ YBP the sediments changed to having a higher organic content for a short period before again changing to a significantly lower organic content at $\approx 1768$ YBP. At $\approx 1334$ YBP the sediments made another significant switch to higher organic content until finally changing significantly at $\approx 80$ YBP to lower organic content. Although organic matter began to increase at 108 YBP, this change was not identified as a long-term, statistically significant transition.

Diatom community shifts

The diatom community contained 84 species from 36 genera (Appendix 1) and was highly plastic throughout the depths of the Jewel Lake core. PCA extracted two useful axes for further analyses, which cumulatively accounted for ca. 55% of the total community variance; PC1 accounted for 34.6% of the variance within the diatom community (Fig. 5), and PC2 accounted for 20.1% of the variance (Fig. 6). PC3 accounted for only 5.9% of the variance and was omitted from further analyses.
FIG. 4. Organic content-depth profile for the Jewel Lake core determined by loss on ignition (LOI). The line with small, opaque circles is the original % organic matter data. The dashed line is the linear regression of % organic matter, which is an important component in calculating zero crossings of the derivative. The other solid lines are the SiZer family of bandwidths in the $\log_{10}(h) = 1.79$ to 2.36 spectra. The open circles indicate points of significant change based on zero crossings of the derivative. The break indicates the region of the core dominated by glacial flour. This region was omitted for visual purposes.
FIG. 5. Diatom PC1-depth profile for the Jewel Lake core. The line with small, opaque circles is the original diatom PC1 data. The dashed line is the linear regression of the diatom PC1 data, which is an important component in calculating zero crossings of the derivative. The other solid lines are the SiZer family of bandwidths in the $\log_{10}(h) = 1.79$ to 2.71 spectra. The open circles indicate points of significant change based on zero crossings of the derivative.
FIG. 6. Diatom PC2-depth profile for the Jewel Lake core. The line with small, opaque circles is the original diatom PC2 data. The dashed line is the linear regression of the diatom PC2 data, which is an important component in calculating zero crossings of the derivative. The other solid lines are the SiZer family of bandwidths in the $\log_{10}(h) = 1.79$ to 2.71 spectra. The open circles indicate points of significant change based on zero crossings of the derivative.
Four diatom species were strongly associated with PC1 (communalities > 0.50; Tables 2 and 3, Fig. 7). Two of these were small-bodied species of the former genus *Fragilaria sensu lato* (currently named *Pseudostaurosira brevistriata* and *Staurosira construens* var. *venter*), which negatively loaded along the axis. These two species are among those typically indicative of cold conditions and their decline is linked to warming (Table 1). Conversely, PC1 is positively loaded by the species *Cymbella diluviana* and *Nitzschia denticula*. These genera are among those that often increase their abundance during warming conditions (Table 1). Because these four major species loadings along PC1 correspond with the predictions of Smol (1983, 1988), Smol et al. (2005), and Smol and Douglas (2007), the PC1 axis as a whole can generally be associated with the suite of temperature changes listed in Table 1. As the PC1 scores become more negative, the relative abundances of *P. brevistriata* and *S. construens* var. *venter* increase, which are indicators of cold conditions; their decline is indicative of warming (as PC1 scores become more positive). Also, as PC1 scores become more positive, the relative abundances of *C. diluviana* and *N. denticula* increase, which are indicators of warming conditions; likewise, their decline is indicative of cooling (PC1 scores become more negative).

SiZer indicated that there were 10 significant changes in the diatom community along the ca. 4300-year continuum. Between \(\approx 4100-3825\) YBP, diatoms significantly changed to more negative PCA scores (from ca. -1 to ca. -2). After this, between \(\approx 3825-3535\) YBP, the diatoms significantly changed to more positive PCA scores (ca. -1 to ca. +0.5). Between \(\approx 3535-3350\) YBP, diatoms again significantly shifted towards more negative PCA scores (ca. -1 to ca. -1.5). Subsequently, between \(\approx 3350-2670\) YBP, there was a longer span when diatom scores became significantly more positive (ca. -1 to ca. +1) than the previous intervals. Conversely, between \(\approx 2670-955\) YBP, there was a significant long-term trend toward more negative PCA scores (ca. 38
TABLE 2. The five diatom species with the greatest individual loadings (cutoff was \( \pm 0.100 \) because these species loadings had communalities \( > 0.50 \)) on the first two principal component analyses axes.

<table>
<thead>
<tr>
<th>Taxon</th>
<th>PC1 loadings</th>
<th>PC2 loadings</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Pseudostaurosira brevistriata</em>&lt;sup&gt;1&lt;/sup&gt;</td>
<td>-0.149</td>
<td>0.047</td>
</tr>
<tr>
<td><em>Staurosira construens var. venter</em>&lt;sup&gt;1&lt;/sup&gt;</td>
<td>-0.194</td>
<td>0.039</td>
</tr>
<tr>
<td><em>Cymbella heteroplueria</em>&lt;sup&gt;2&lt;/sup&gt;</td>
<td>-0.032</td>
<td>-0.232</td>
</tr>
<tr>
<td><em>Cymbella diluviana</em>&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.112</td>
<td>0.006</td>
</tr>
<tr>
<td><em>Nitzschia denticula</em>&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.133</td>
<td>-0.040</td>
</tr>
</tbody>
</table>

Notes: <sup>1</sup>Genera that are reported to be typical in colder waters and are reduced in abundance as waters become warmer; <sup>2</sup>Genera that are reported to increase their abundance as waters become warmer (Smol et al. 2005, Smol and Douglas 2007)
TABLE 3. Pearson correlation coefficients between percent organic matter, the five predominant diatom species, and the first two diatom PCA axes. Bold typeface indicates a significant correlation.

<table>
<thead>
<tr>
<th>% organic matter</th>
<th>P. brevistriata</th>
<th>S. construens var. venter</th>
<th>C. heteropleura</th>
<th>C. diluviana</th>
<th>N. denticula</th>
<th>Diatom PC1</th>
<th>Diatom PC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>% organic matter</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P. brevistriata</td>
<td>-0.09</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S. construens var. venter</td>
<td>-0.12</td>
<td>0.62</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. heteropleura</td>
<td>-0.33</td>
<td>-0.20</td>
<td>-0.09</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. diluviana</td>
<td>0.12</td>
<td>-0.44</td>
<td>-0.49</td>
<td>-0.34</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N. denticula</td>
<td>0.11</td>
<td>-0.31</td>
<td>-0.45</td>
<td>-0.57</td>
<td>0.40</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Diatom PC1</td>
<td>0.12</td>
<td>-0.77</td>
<td>-0.91</td>
<td>-0.13</td>
<td>0.66</td>
<td>0.60</td>
<td>1.00</td>
</tr>
<tr>
<td>Diatom PC2</td>
<td>0.21</td>
<td>0.33</td>
<td>0.21</td>
<td>-0.95</td>
<td>0.27</td>
<td>0.37</td>
<td>0.00</td>
</tr>
</tbody>
</table>
FIG. 7. Relative abundance-depth profiles for the five species of diatoms with the most predominant loadings from PCA within the Jewel Lake core. The dashed lines are the linear regressions of the diatom relative abundance data, which are important components in calculating zero crossings of the derivative. The other solid lines are the SiZer bandwidths (see text for spectra). The open circles indicate points of significant change based on zero crossings of the derivative.
-0.5 to ca. -2); this long-term trend was briefly interrupted by a short, significant change to more positive PCA scores (up to ca. +0.75) between \(\approx 1660-1570\) YBP before again decreasing to the lowest nadir along the entire series at \(\approx 1232\) YBP. A rapid, significant transition towards more positive PCA scores (from ca. 0 to ca. +2) occurred between \(\approx 955-300\) YBP. For a brief period, between \(\approx 300\) YBP-170 YBP, the scores became significantly less positive (from ca. +0.7 to ca. 0). After this brief trend, the diatoms significantly became more positive (up to ca. +2) for the remainder of the time series.

Only one diatom species, *C. heteropleura* (-0.232), was dominantly loaded along the PC2 axis (Tables 2 and 3, Fig. 6). As PC2 scores become more negative, the relative abundance of *C. heteropleura* increases. While increases in the genus *Cymbella* may be considered an indicator of recent warming conditions (Smol et al. 2005, Smol and Douglas 2007, Table 1), the *C. heteropleura* in the Jewel Lake core do not seem to have any significant changes in association with recently layered sediments. Rather, the largest change in PC2 and, subsequently, *C. heteropleura* occurred between \(\approx 3272-1850\) YBP. SiZer indicated that this was a significant transition, with a spread of PCA scores ranging from ca. 0 to ca. -3.5. This transition towards more negative PCA scores (increasing *C. heteropleura* abundance) enveloped the glacial flour disruption in the sedimentary record between depths 545-700 mm, so it is possible that *C. heteropleura* and PC2 are capturing variance associated with turbidity in the water column. However, because PC2 was only dominated by one species and was not as insightful as PC1, all of my temperature-induced, community-level interpretations were from PC1.

The five diatom species with the highest PCA loadings along PC1 and PC2 were highly plastic in their relative abundances through time (Fig. 7). Each of these five species demonstrated significant SiZer changes in abundance throughout the time series.
Representatives from the former genus, *Fragilaria sensu lato* (now *P. brevistriata* and *S. construens var. venter*), consistently had the highest relative abundances (up to ca. 66% individually and ca. 91% when combined) of all the species. *C. heteropleura* had mostly low relative abundances except between ≈ 3160-1905 YBP when it peaked at ca. 75% of the total community. *C. diluviana* and *N. denticula* generally demonstrated lower relative abundances than the other three dominant taxa throughout the entire core.

The relative abundance of *P. brevistriata* had eight significant changes along the long-term time series. SiZer (bandwidths in the log$_{10}[h] = 1.79$ to 2.48 spectra) indicated that the relative abundance of *P. brevistriata* significantly increased between ≈ 4070-3750 YBP, ≈ 3550-3200 YBP, ≈ 1684-913 YBP, and ≈ 340-244 YBP. Conversely, between these increasing intervals, the relative abundances significantly decreased from ≈ 3750-3550, ≈ 3200-1684 YBP, ≈ 913 YBP-340 YBP, and ≈ 240 YBP to present day.

*S. construens var. venter* had a similar relative abundance profile as *P. brevistriata*. SiZer (bandwidths in the log$_{10}[h] = 1.79$ to 2.59) spectra indicated that the relative abundance significantly increased between ≈ 4165-3730 YBP, ≈ 3500-3330 YBP, ≈ 2250-892 YBP, and ≈ 210-190 YBP. Conversely, relative abundances significantly decreased between ≈ 3330-2250 YBP, ≈ 892-210 YBP, and ≈ 190 YBP to present day.

The relative abundance profile of *C. heteropleura* was unimodal. Throughout most of the core, relative abundances were low, but between ≈ 3160-1900 YBP, the relative abundance significantly increased (SiZer bandwidths in the log$_{10}[h] = 1.79$ to 2.71 spectra) to up to the apex of the mode, which was ca. 75% of the entire diatom community.

The relative abundances of *C. diluviana* were the lowest of the five most dominant taxa and SiZer indicated that this diatom had six significant transitions in abundance through time.
Relative abundances significantly decreased between \( \approx 3450-1608 \) YBP, \( \approx 1532-1078 \) YBP, and \( \approx 861-190 \) YBP. Conversely, relative abundances significantly increased between \( \approx 1608-1532 \), \( \approx 1078-861 \) YBP, and \( \approx 190 \) YBP to present day.

*N. denticula* had a similar relative abundance profile as *C. diluviana*. Also, SiZer indicated six significant transitions throughout the core (bandwidths in the \( \log_{10}[h] = 1.79 \) to 2.59 spectra). *N. denticula* had significantly lower number between \( \approx 3250-1726 \) YBP, \( \approx 500-1154 \) YBP, and \( \approx 355-134 \) YBP. Between these nadirs, *N. denticula* had alternations of significantly higher abundances before \( \approx 3250 \) YBP and during the intervals between \( \approx 1726-1500 \) YBP, \( \approx 1154-355 \) YBP, and \( \approx 134 \) YBP to present day.

*Cross-correlation*

In addition to using SiZer to identify significant transitions in the diatom community through time, I used cross-correlation analysis to test the relationship between temperature changes (paleo-thermometer of Hu et al. [2001]) and diatom changes. Over the overlapping 2000 years of the paleo-thermometer and diatom PC1, both series were significantly cross-correlated at zero lag \( r = 0.32, p < 0.05 \), which was also the strongest correlation point (Fig. 8). This correlation implies that as temperatures decline, diatom PC1 concomitantly becomes more negative with minimal lag, and vice versa.

*Time series forecast*

I modeled the diatom PC1 data using an autoregressive, integrated moving average (ARIMA, Fig. 9) model to forecast a potential diatom community up to 240 years into the future.
FIG. 8. Cross-correlation between the temperature data from Hu et al. (2001) and diatom PC1.
FIG. 9. Diatom PC1-depth profile with ARIMA analyses for the Jewel Lake core. The dotted lines are the original diatom PC1 data. The line with small, opaque circles is the modeled PC1 ARIMA data with forecast data (20 steps, 240 years). The model was adequate (AR[1] $T = 20.2$, $P < 0.0001$, MA[0]). The error bars are the sum of both upper and lower 95% confidence intervals surrounding the forecast data. Only the error bars at the beginning and end of the forecasted data are shown for visual convenience. All of the removed error bars (18 removed bars) lie between the ranges indicated in the figure above.
I did not model the PC2 data because that series was unimodal and appeared to asymptote over the most recent 1500 years, negating any insight gained from the ARIMA approach. The most adequate model (best prediction power) had a first-order auto-regressive function and the moving average function removed (AR[1] $T = 20.2, P < 0.0001$, MA[0]). I ran an additional model that included a first-order moving average function that was adequate, but the model’s predictive power was not as strong (AR[1] $T = 15.8, P < 0.0001$, MA[1] $T = 0.7, P = 0.5$) as the first model; therefore, only the first model was considered for further analyses. The model forecast 20 time steps (each step = 12 years) into the future. There were considerable confidence intervals around the projections, but the model predicted a slight decrease in PC1 scores until 96 years into the future, and the model projected slight increases in PC1 scores until the end of the series 240 years into the future after this nadir (Fig. 9).

DISCUSSION

The main objective of my study was to generate an alternative temperature change regime for sub-arctic Alaska using diatoms to test specifically and extend a generalized suite of arctic diatom predictions about responses to rapid warming (Table 1). The meta-analyses of Smol et al. (2005) and Smol and Douglas (2007) based on the working hypotheses of Smol (1983, 1988) have compared environmentally calibrated sets of rapidly changing diatom community structures across the arctic to known thermometer temperature increases over matching periods. From those analyses, they created a suite of potential diatom species and genera profiles that are predicted to respond to rapid warming in the high arctic (Table 1). These predictions are based on many factors tied to ice cover, thermal stratification, nutrient availability, and habitat availability, but they can be summarized to indicate that during warming
conditions, the diatom community is expected to change its life strategy from benthic to planktonic (Smol et al. 2005). Their data supported their hypotheses because they showed that diatoms changed as predicted in arctic regions experiencing rapid warming, whereas diatoms did not change in regions that were not warming.

I tested if those diatom predictions about responses to recent, rapid warming could also be applied in reverse under conditions of cooling in my sub-arctic study lake. In other words, under conditions of cooling, would the diatoms change their life strategies from planktonic to benthic? To validate my diatom record and infer temperature-induced trends, I used the paleo-thermometer record of western Alaska reported in Hu et al. (2001) (Fig. 2), which was calibrated from a lake in close proximity (306 km) to Jewel Lake. However, the paleo-thermometer goes back 2000 YBP and my diatom record extends ca. 4300 YBP. To account for this difference, I compared my diatom record from ca. 4300-2000 YBP with the global climate interpretations reported in Lamb (1977), Bond et al. (1997), and Mayewski et al. (2005). Ultimately, my results were validated by the paleo-thermometer and were also generally supported by the other temperature trends reported in the literature.

The insights gained from using SiZer analyses of the diatom community permitted statistical identification of specific points in time when the community significantly changed from one dominant profile to another. Specifically, the use of SiZer elucidated when the major indicator diatoms of Jewel Lake statistically shifted their life strategies from benthic to planktonic, and vice versa. Then, these diatom shift points could be visually compared to extraneous forces, such as temperature, to infer concordant bifurcations. If temperature switch-points were within close proximity of diatom bifurcations, then there would be evidence
supporting temperature-induced diatom changes. These data are discussed in further detail below.

Sedimentary organic matter

Before interpreting diatom community structure, it is insightful to explore sedimentary organic matter content (Fig. 4), which is a useful surrogate for estimating changes in primary production. Decreases in organic matter often signify lower production and vice versa, which may be caused by changes in water temperature (Wetzel 2001, Cohen 2003). There were statistically significant transitions in organic matter along the continuum. A significant decrease occurred between $\approx 2798$-1976 YBP, which suggests lower production, possibly associated with cold temperatures. This decrease in organic matter is concordant with the cold climate boundary of 2700 YBP described by Lamb (1977) and the cold period of the North Atlantic determined by Bond et al. (1997).

Furthermore, the sedimentary characteristics of Jewel Lake are in general agreement with the regional, western Alaska paleo-climate record of Hu et al. (2001). Between $\approx 1976$-1768 YBP, the percentage of organic matter significantly increased compared to the previous profile, which is consistent with the warm temperatures between 2000-1650 YBP described by Hu et al. (2001). Additionally, Hu et al. (2001) indicated there was a major cold period between 1650-945 YBP; the organic matter of Jewel Lake sediments significantly decreased between $\approx 1768$-1334 YBP. However, while the organic matter did have intermittent peaks of increases between $\approx 1334$-600 YBP that coincided with warming from both the records of Hu et al. (2001) and Mayewski et al. (2004), they were not statistically significant transitions or trends. Likewise, the organic matter from $\approx 300$ YBP to present day does not directly correspond to any known
Temperature shifts on a decade-per-decade basis. While the general trajectories of the organic matter profile (Fig. 4) and diatom PC1 (Fig. 5) are similar in shape, which indicates a possible relationship between diatom composition and overall primary production, there is an asynchrony between the trajectories. Specifically, reductions in organic matter appear to precede reductions in PC1 scores, but increases in organic matter follow increases in PC1 scores. A post-hoc cross-correlation revealed no significant relationship at the zero lag (Table 3), but did indicate a significant correlation at ca. 200 years. This correlation is likely a statistical artifact and has no coherent ecological interpretation. These anomalies in organic matter may be the result of reduced proxy utility and resolution, diagenesis altering the sedimentary profile over time, or from a time offset decoupling diatom dynamics to overall primary production. These potential sources of error and asynchrony are further exemplified by the low correlation coefficients between organic matter and all diatom variables (Table 3). Since diatoms do not suffer from asynchronous time effects, they are of higher resolution and provide for more robust analyses of temperature changes (Smol 1988).

**Temperature-induced diatom community shifts**

The diatom characteristics of Jewel Lake showed significant changes through time, and mechanisms influencing these shifts are supported by the temperature-genera profiles of Smol (1983, 1988), Smol et al. (2005), and Smol and Douglas (2007). The entirety of my temperature-induced, community-level diatom analysis is based on interpretations of diatom PC1, which, as a newly derived variable, collectively represents a factored interpretation of the prevailing community characteristics. Jewel Lake diatom PC1 was dominated by *P. brevistriata*, *S. construens* var. *venter*, *C. diluviana*, and *N. denticula* (Table 2). Benthic *Pseudostaurosira* and
Staurosira are predicted to decline under warming conditions at the expense of Cymbella and planktonic Nitzschia (Table 1). Cymbella is considered an artificial genus (Wehr and Sheath 2003), but many species within this superfluous group are often benthic, but notable exceptions have been shown to increase rapidly their abundance during periods of warming (Rühland and Smol 2005, Smol et al. 2005, and Smol and Douglas 2007). In Jewel Lake, P. brevistriata was highly variable, but showed its lowest relative abundance during the last 150 years. Likewise, S. construens var. venter had a similar nadir as P. brevistriata. In contrast, C. diluviana showed its greatest relative abundances during the last 150 years. Also, N. denticula showed a significant increase over this period. Because the dominant species profiles of Jewel Lake were similar to the data of the last 150 years presented in Smol et al. (2005) and Smol and Douglas (2007) and were correlated with the temperatures reported by Hu et al. (2001), I concluded that these species shifts in Jewel Lake are reliable surrogates of temperature changes. Therefore, as PC1 scores become more negative, the diatom community shifted towards a colder water, more benthic assemblage, and when PC1 scores become more positive, the diatom community shifted towards a warmer water, more planktonic community. Using these PC1 interpretations, it should then be possible to infer temperature changes along the entirety of the sediment core, dating back to ca. 4300 YBP.

Diatom PC1 from Jewel Lake (Figs. 5 and 10) suggested the diatoms significantly changed to colder water assemblages between $\approx 4100-3825$ YBP, $\approx 3535-3350$ YBP, $\approx 2670-1660$ YBP, $\approx 1570-955$ YBP, and $\approx 300-170$ YBP; the diatoms shifted to warmer water assemblages between $\approx 3825-3535$ YBP, $\approx 3350-2670$ YBP, $\approx 1660-1570$ YBP, $\approx 955-300$ YBP, and from $\approx 170$ YBP to present. This interpretation had strong visual correspondence with the paleo-thermometer of Hu et al. (2001) from ca. 2000 YBP to present day (Fig. 10). Specifically,
FIG. 10. Relationships between diatom PC1 and documented Holocene temperature shifts. The top panel are the data of Hu et al. (2001) (same as Fig. 2). The bottom panel is the diatom PC1 data (same as Fig. 5).
the major indicator diatoms of Jewel Lake repeatedly shifted their life strategies to benthic during documented cold periods and to planktonic during documented warm periods. The paleo-thermometer of Hu et al. (2001) inferred a significant cooling trend between 1650-945 YBP, which had very similar significant zero crossings as diatom PC1 (≈ 1570-955 YBP) (Fig. 10). Also, the paleo-thermometer indicated a significant warming trend between 945-680 YBP, which approximates the Jewel Lake diatom PC1 inferred warming trend between ≈ 955-300 YBP. Slight deviations in dates between the series may have been caused by overlapping error rates in the ^14^C dating method, which could be up to 150 years (maximum error rate in Jewel Lake = ± 50 years; see Hu et al. [2001] for more details). There is a slight decoupling between the end of the warming trend inferred by Hu et al. (2001) at 680 YBP and the diatom PC1 inferred end at ≈ 300 YBP. This asynchrony may be a statistical artifact of SiZer time series fitting because SiZer only calculates significant bifurcation points. The diatom PC1 progression from warm to cold originated at ≈ 750 YBP, which is in close alignment with the Hu et al. (2001) switch-point of 680 YBP. It is likely that the diatoms were switching from planktonic to benthic before SiZer indicated a significant bifurcation point.

As a more rigorous test of correspondence between the paleo-thermometer (Hu et al. 2001) and diatom PC1, I performed cross-correlation analyses. The strongest correlation was at zero lag (r = 0.32, p < 0.05) (Fig. 8), which suggests that temperature changes had an almost immediate effect on the diatoms of Jewel Lake, despite any visual decoupling as described above. This immediate temperature effect on diatoms was predicted in the work of Smol (1983, 1988) and was demonstrated in my analyses of Jewel Lake. Ultimately, through the visual corroboration from SiZer bandwidths and the significant cross-correlation, diatom PC1 temperature changes are validated by the paleo-thermometer of Hu et al. (2001). There is
remarkable correspondence between the two records, which is exciting since each proxy type is so different.

Also, from ca. 4300-2000 YBP, diatom PC1 also had general correspondence with global climate interpretations reported in the literature (Fig. 10). The diatom PC1 inferred temperature decrease at ≈ 2670 occurred very closely after the cold global climate boundary at 2700 YBP identified by Lamb (1977). Furthermore, diatom PC1 inferred cold trends closely matched the cold climate boundaries of Bond et al. (1997), with concordant cold periods originating near 4200 and 2800 YBP. Diatom PC1 also had agreement with the cooling period between 4200-3800 YBP reported by Mayewski et al. (2004). However, diatoms oscillated three times between ≈ 3350-2670 YBP, which was enveloped by an extensive polar cold period (3500-2500 YBP) reported by Mayewski et al. (2004).

The few discrepancies between diatom PC1 and the polar trends described by Mayewski et al. (2004) between ≈ 3500-2500 YBP (Fig. 10) were likely caused by variations in regional climates compared to the global climate aggregate. For example, LaMarche and Mooney (1967) demonstrated that the climate of the western United States experienced a warm period ca. 3267 YBP by showing altithermal tree line advances consistent with warming, which is in agreement with the Jewel Lake diatom-inferred warming trend between ≈ 3350-2670 YBP. Also, Lawson et al. (2007) documented major glacial advances in Glacial Bay, Alaska, that terminated at ca. 3200 YBP. This record implies some level of warming occurred after 3200 YBP, which correspond with Jewel Lake diatom-inferred warming between ≈ 3350-2670.

While diatom PC2 (Fig. 6) accounted for a modest proportion of the community variance (20.1%), it most likely cannot be considered as a representation of temperature change. Only one species, *C. heteropleura*, dominantly loaded along PC2 (Tables 2 and 3). Much of this
species’ autecology is undocumented, other than it appears to be benthic. In Jewel Lake, *C. heteropleura* was the most dominant taxon recorded between ≈ 2900-2100 YBP. This period encompasses two important features of the environment. First, it includes the cold climate boundaries described by Lamb (1977) and Bond et al. (1997). Therefore, it is possible that *C. heteropleura*, because it is a benthic taxon, was increasing in numbers during this cooling spell, consistent with the general benthic predictions of Smol (1983, 1988). Second, this time series also enveloped the glacial flour influx into the lake, which probably caused more turbidity and sedimentation within the lake than normal. As such, because *C. heteropleura* is large-bodied (up to ≈ 270 µm), its large size may have given the species an advantage in benthic environments during periods of heavy sedimentation. Future studies on this species can resolve this question. Nonetheless, PC2 will likely remain as a weak representation of temperature change, at best, until more information about *C. heteropleura* can be documented.

My final component to assessing the predictions of Smol (1983, 1988), Smol et al. (2005), and Smol and Douglas (2007) was modeling potential future diatom assemblages in Jewel Lake with the ARIMA approach (Fig. 9). Those four studies have suggested that many arctic lakes have already crossed critical ecological thresholds as a direct result of rapid polar warming. They documented drastic species shifts documented in Table 1, and predicted that this trend will continue more rapidly into the future. I applied ARIMA to my PC1 diatom series to estimate community-level responses into the future based on the model assumption that the Jewel Lake diatoms showed changes within the last 150 years consistent with warming. However, while the model was statistically adequate and was able to predict a future trend, the predicted changes initially showed a tendency to decrease in PC1 score (colder) before showing a modest increase towards more positive PC1 scores (warmer). This prediction of warming was
promising, but the slope of the warming trend was not as steep as previous warming trends along
the continuum. ARIMA models use both autoregressive and moving average functions;
therefore, by definition, each point in the model is directly dependent on the previous point in the
series. Since the actual diatom PC1 demonstrated a slight nadir in scores during the most recent
50 years, although the existing SiZer trend was on a significant upward transition, the model was
required to account for this decrease before projecting any future increases. In this case, it
appears that the utility of the ARIMA approach was not insightful. However, this does not
preclude ARIMA as a potential tool in other diatom analyses.

Conclusions

Changes in Jewel Lake diatoms showed strong concordance with temperature
oscillations, a finding that was corroborated by statistical validation from the paleo-thermometer
of Hu et al. (2001) and comparison to both global and regional climate interpretations from the
literature. My analyses were able to support my first hypothesis and resolve temperature-
dependent diatom changes over the length of the core. However, I was unable to support fully
my second hypothesis that stated Jewel Lake diatoms, as a communal aggregate, would respond
the most drastically to warming within the last 150 years when compared to the entire time
series. While some individual diatom species did change significantly in response to recent
warming over the most recent 150 years (Fig. 7), the change in multivariate PC1 representation
of the diatoms over the last 150 years was no greater than any of the other previous warming
conditions along the ca. 4300-year length of PC1.

This diatom PC1 result could be caused by several factors. First, it is possible that PCA
dampened major changes and amplified small changes. By definition, PCA assumes large
variances represent large dynamics, but some of these dynamics could have been lost because PCA often involutes the ends of the axes. This is highly relevant because the most recent 150 years are at the end of the PC1 axis. Second, it is possible that the sub-arctic has had more warming periods in the past than the arctic, minimizing the appearance of the severity of recent warming. Third, it is possible that the sedimentary layers (5 mm) were too thick to capture small incremental changes and to resolve noise over short periods. However, it is most likely that the sub-arctic probably has not warmed as much, or as quickly, as the high arctic. The ARIMA model of Jewel Lake diatoms predicted a slight increase in planktonic diatoms, but if actual warming and diatom shifts had been more drastic, the model would have predicted a more rapid transition. The ARIMA model has, however, demonstrated utility in assessing lacustrine environments at, or near, critical thresholds. Since the diatoms in Jewel Lake have been responding to warming over the last \( \approx 150 \) years, and ARIMA predicted additional warming responses (with a lag), Jewel Lake is likely near a critical tipping point similar to those already reported by Smol et al. (2005) and Smol and Douglas (2007) for high arctic lakes.

In conclusion, the research presented here made incremental advancements for using diatoms as climate surrogates and offers insights for future research directions. I was able to test quantitatively null hypotheses of changes in the diatom community, identify significant bifurcations, and statistically validate paleo-diatom assemblages with an independently derived paleo-thermometer. The use of these quantitative evaluation methods reduced the probability of falsely accepting erroneous, outlying data as ecologically and statistically significant. Furthermore, the combination of multivariate ordination, statistical treatment, and time series modeling makes diatom paleo-limnology highly amenable for the growing focus of modeling ecological regime shifts. Specifically, these treatments permit calculation of community
variance before and after bifurcations in the diatom community, which is essential for deciphering leading indicators of regime shifts. Recent studies (e.g. Carpenter and Brock 2006 and Carpenter et al. 2008) were able to show that increasingly rising variance along a continuum was a reliable indicator of catastrophic regime shifts. Such a powerful technique presents a valuable tool for limnologists to use in future analyses. Additionally, further development and refinement of time series analyses (such as SiZer and ARIMA) could better indicate significant changes, including variance along the time continuum, especially over shorter time spans such as the rapid warming in the arctic. Combining these techniques would provide more refined forecasting tools and would be invaluable towards assessing the current status of many of our imperiled aquatic resources.
LITERATURE CITED


APPENDIX 1. List of the 82 diatom species documented in Jewel Lake, Alaska. The relative abundances reported refer to the maximum proportion of each species found in any one of the 194 sediment samples along the entire core.

<table>
<thead>
<tr>
<th>Species</th>
<th>Maximum relative abundance in any sample</th>
</tr>
</thead>
<tbody>
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CHAPTER TWO: A VALIDATED DIATOM-INFERRED RECORD OF SOLAR-MODULATED DROUGHT SPANNING THE LAST TWO MILLENNIA
IN NORTHERN NEW MEXICO, USA

Abstract. I investigated mid-to-late Holocene (2000 YBP to present) precipitation in northern New Mexico, USA, using diatom frustules sampled from a lake sediment core. Diatoms were analyzed with a combination of multivariate ordination and time series analysis to identify significant changes in community dynamics and corresponding significant bifurcations between periods of increased and decreased precipitation. This diatom-inferred precipitation regime was statistically corroborated against an independently derived tree ring record of precipitation in northern New Mexico. Also, both the tree ring and diatom records were tested for concordance with historical solar intensity data. Diatom and tree ring records were both significantly cross-correlated with solar intensity. Periods of drought generally aligned with periods of decreased solar intensity during ≈1400-1000 and ≈600-200 YBP; periods of increased solar activity generally aligned with periods of increased precipitation during ≈1000-600 YBP and ≈200 YBP to present day. These results suggest that drought regimes in northern New Mexico were modulated by cycles of decreased solar activity. Also, the most recent 200 years have been a period of relative wetness. These conclusions are the opposite of speleothem data interpreted from southern New Mexico. Possible explanations for these discrepancies along a north-south differential are discussed.
INTRODUCTION

Study background

Droughts, and their subsequent ameliorations, have been a prominent landscape feature of the southwestern United States (USA, hereinafter) and Mesoamerica for at least the last three millennia (Woodhouse and Overpeck 1998, Polyak and Asmerom 2001, Cook et al. 2004, Hodell et al. 2001, 2005, Rasmussen et al. 2006). While there is some asynchrony among various historical drought reconstructions (Oladipo 1986, Woodhouse and Overpeck 1998, Laird et al. 1998, Betancourt et al. 2002), it is widely accepted that droughts were major drivers in the demise of ancient civilizations in those regions (Hodell et al. 1995, 2001, 2005 Polyak and Asmerom 2001, Shaw 2003). More recently, droughts have had tremendously damaging impacts on the economic, social, political, and environmental components of many currently inhabited regions throughout the central and southwestern USA (Rosenberg 1978, Karl and Koscielny 1982, Riebsame et al. 1991). Important examples of these damages are the Dust Bowl of the 1930s (79 YBP) and the droughts of the 1950s (59 YBP).

Heightened concerns over potential water exhaustion from anthropogenic climate change (e.g. Yu and Ito 1999) have prompted several southwestern USA states to draft drinking water plans (D’Antonio 2006). These concerns are founded from new forecasts for the southwestern USA that project an imminent transition to a new, hyper-arid climate caused by anthropogenic greenhouse forcing (WCRP 2003, Cook et al. 2004, Seager et al. 2007). However, other climate models show considerable disagreement in their precipitation projections, particularly within sub-tropical regions (Felzer and Heard 1999, Houghton et al. 2001). Nevertheless, because the southwestern USA is a densely populated region with high water demand (Sukhwal 1987, Lins and Stakhiv 1999, Gleick and Chalecki 2000, D’Antonio 2006), it is paramount to understand
thoroughly the historical, baseline patterns of drought and their possible causes. Specifically, in order to make more robust predictions of possible precipitation deficits, many long-term, pre-industrial age records are needed from many regions to account for any potential human-induced changes from normal drought cycles. Non-anthropogenic climate changes typically follow known intervals, whereas anthropogenically caused changes would be highly anomalous and non-cyclical (Barry and Chorley 1999). For example, changes in solar forcing (Reimer et al. 2004) over the last two millennia have been demonstrated to cause ca. 400-year intervals of drought and recovery (Yu and Ito 1999); anthropogenic effects may intensify and/or prolong this baseline drought pattern (D’Antonio 2006).

Despite the need for historical climate data, instrument records prior to AD 1880 (129 YBP) are rare, which necessitates paleo-proxy interpretations (Cohen 2003). When constructing historical, regional paleo-climate regimes, it is often important to have proxy data from several material sources because each proxy type has its own associated strengths, weaknesses, and sensitivities (Woodcock 1992, Cohen 2003, Betancourt et al. 2002, von Storch et al. 2004). For instance, a comparison of tree ring proxies from northern New Mexico, USA (Grissino-Mayer 1995, 1996) and speleothem proxies from southern New Mexico (Polyak and Asmerom 2001, Polyak et al. 2001, Rasmussen et al. 2006, Asmerom et al. 2007) over corresponding time series showed asynchrony in both temporal variation and overall sensitivity to precipitation (cf. Betancourt et al. 2002). Moreover, the tree ring reconstructions and the speleothem reconstructions differ in their interpretations of the nearly modern (200-0 YBP) climate analog. The tree ring data (Grissino-Mayer 1995, 1996) suggest that the most recent two centuries (200 YBP) have been a period of relative wetness with more precipitation than the long-term average, whereas the speleothem data (Polyak and Asmerom 2001, Polyak et al. 2001, Rasmussen et al. 2006).
2006, Asmerom et al. 2007) suggest the nearly modern analog is similar to, or slightly drier than, the climate from the long-term past. Furthermore, the speleothem data from southern New Mexico (Asmerom et al. 2007) suggest patterns of increased solar intensity induced droughts, but lake sediment data from North Dakota, USA (Yu and Ito 1999) suggest the opposite interaction. These discrepancies indicate a potential north-south gradient in drought cycles and their potential causes within the USA. Consequently, there is justification for additional paleo-climate analyses in New Mexico, and perhaps the southwestern USA as a whole, that use alternative proxies.


Study objective and hypotheses

The overall objective of my study was to create an alternative paleo-drought record from New Mexico using diatoms sampled from lake sediments to test the hypothesis that drought conditions changed the diatom community. I also explored the relationship between changes in solar intensity generated from previous studies (Reimer et al. 2004) and diatom community structure from my study in order to understand solar forcing as a mechanism in the establishment of cyclical drought patterns in New Mexico. The following two hypotheses were tested:

H\textsubscript{1}: Drought conditions changed diatom community structure in my study lake. The diatom community will be highly plastic throughout the length of the core (ca. 2000 years), demonstrating statistically significant community changes that align drought patterns.

H\textsubscript{2}: Change in solar intensity changed the diatom community structure in my study lake. Effects from solar changes cascaded to the prevailing climate, ultimately changing diatom community structure.

As part of the overall approach to resolve these hypotheses, I applied uses of new statistics to the diatom assemblage data set to test for significant transitions in the diatom community through time. I also validated the diatom inferences generated in the study against an
independently derived record of drought from tree rings from northern New Mexico (Grissino-Mayer 1995, 1996). Finally, the study results provided a supplement to the diatom-inferred Holocene climate archive with a study site from New Mexico, which is an underrepresented area when compared to other locations.

**Study importance**

This study employs an application of statistical analyses on diatom community dynamics over long-term time series. Diatom paleo-limnology studies typically have not used statistical time series analyses to determine quantitatively significant changes in the community through time. I suggest that incorporating statistics into diatom analyses should be a priority in diatom-inferred climate reconstructions. The ability to collect large amounts of data from many variables over long-term time series is one of the most visible strengths of paleo-limnology. However, long-term time series, especially biological sources of climate proxies, often have significant amounts of covariance (Woodcock 1992) and noise (von Storch et al. 2004). Covariance and noise can dilute actual trends and/or produce type-1 errors by creating the appearance of changes when none are statistical realities. In order to test rigorously the ability of diatoms to indicate paleo-drought conditions, especially when they are tested for validation against independently derived records of tree rings, it is absolutely necessary to account statistically for noise in the data and to identify actual data trends. Specifically, because diatoms are often cosmopolitan with rapid dispersal, it is paramount to calculate statistically whether a population emergence or decline is a random, noisy phenomenon or if it is conclusively linked to some concomitant environmental process. Diatom paleo-limnology studies have traditionally been highly descriptive and informative, but a need for quantitative null hypothesis testing
remains. My approach is the first diatom paleo-limnology analysis to use a newly derived time series analysis (SiZer [Zhang and Marron 2005, Rondonotti et al. 2007]) in order to filter out noise and calculate statistically significant changes in diatom communities over time.

Furthermore, my study makes the next incremental advance in diatom-inferred records of drought. Diatoms are thoroughly documented in the literature as robust indicator taxa of drought conditions (Battarbee 1986, Laird et al. 1998, Cohen 2003). Also, paleo-drought records exist in New Mexico, but Holocene diatom-inferred drought records there are scarce. My study allows for a unique opportunity to generate a diatom-inferred record of drought and statistically validate it against an existing paleo-drought record. The substantiation of my diatom-inferred drought record of New Mexico from independently derived records of precipitation and solar activity will improve our understanding of baseline drought conditions, their distribution, and their potential causes, which will aid in our ability to forecast precipitation changes in the vulnerable southwestern USA.

METHODS

Study site

Santa Fe Lake (N 32° 22’ 28.5”, W 103° 21’ 55.1”) is a closed-basin, cirque and alpine lake (surface area = 1.9 ha, maximum depth = 7.0 m, 3530 m above sea level, August pH = 7.4) approximately 28 km northeast of Santa Fe, New Mexico, USA (Fig. 1). Importantly, the lake has a small basin (15.9 ha; lake covers 12% of the entire basin) completely underlain with Precambrian granite, which contributes to a classification as a highly acid sensitive lake (acid neutralization capacity = 5-10 mg/L, calcium hardness = 6-27 mg/L [Lynch et al. 1988]). The lake is located within the Pecos Wilderness Area of New Mexico and is isolated from
FIG. 1. Location map of the study site, Santa Fe Lake, with reference to the site of Grissino-Mayer (1995, 1996) in New Mexico, USA.
Santa Fe Lake, Pecos Wilderness Area

development and experiences minimal perturbation; anthropogenic nutrient inputs (non-atmospheric) are likely low or none. The current mean annual air temperature of the city of Santa Fe is 10.5° C, with a mean January temperature of -0.6° C and a mean July temperature of 21.6° C. The mean annual precipitation is approximately 34.8 cm. Additional information on the lake is reported in Lynch et al. (1988) and supplemental climate data about New Mexico is recorded in Grissino-Mayer (1995) and D’Antonio (2006).

*Paleo-precipitation and solar activity reconstructions*

I used an independently derived record of inferred paleo-precipitation in New Mexico to validate my diatom-inferred precipitation regime. This record was a 2129-year reconstruction of El Malpais National Monument (180 km southwest of Santa Fe Lake) inferred from tree rings analyzed by Grissino-Mayer (1995, 1996). The data are archived on the internet and were downloaded from ftp://ftp.ncdc.noaa.gov/pub/data/paleo/treering/reconstructions/newmexico/malpais_recon.txt.

Also, I used a paleo-reconstruction of solar activity inferred from atmospheric 14C data sampled from tree rings, corals, and foraminifera that were reported in Reimer et al. (2004). These data are also archived on the internet and were downloaded from http://www.radiocarbon.org/IntCal04%20files/intcal04.14c. Changes in 14C are an effective proxy of solar intensity. Production of atmospheric 14C is modulated by cosmic bombardment that causes the beta decay transformation of 14N to 14C. As solar activity increases, the amount of cosmic rays reaching the atmosphere is reduced. Therefore, lower 14C delta values indicate more intense sun activity, and higher 14C delta values indicate lower sun activity.
Sediment core

In August AD 2007 I retrieved a continuous 75 cm sediment core from the deepest portion of the lake by using a 6.5 cm wide core barrel attached to a modified Glew gravity corer (Glew 1989). Upon retrieval, the core was stored at a constant temperature of 4º C until removed for analyses. Within the laboratory, the core was extruded and sectioned into 75 discrete 1 cm sections. Approximately 1 g wet mass was taken from each 1 cm sub-sample for diatom analyses. The remaining portion of each sub-sample was dried at 50º C until a constant mass was obtained. Once a constant mass was obtained, the sub-samples were finely ground with a mortar and pestle. Approximately 1 g dry mass from each 1 cm sub-sample was combusted at 550º C for 24 hours to determine organic content from loss on ignition (LOI). After combustion, samples were weighed, rehydrated with deionized water (18 megohm-cm resistivity), dried, and weighed again to account for any loss of water of hydration.

Additionally, six uncombusted sub-samples from the sedimentary sequence were sent to the National Ocean Sciences Accelerator Mass Spectrometry Facility, Woods Hole, Massachusetts for reservoir-corrected (present day = AD 1950; calibration data from INTCAL 98 [Stuvier et al. 1998]) 14C dating of bulk organic matter taken from the depths of 0 cm (top of core), 15 cm, 30 cm, 45 cm, 60 cm, and 74 cm. These depths were chosen because they were at approximately evenly spaced intervals. The age-depth profile was fitted with cubic spline regression. Because of the extrapolation of estimated dates between each known 14C date, all extrapolated dates will be noted with the symbol “≈” throughout the text. The bottom sample dated to 1902 YBP ± 40 years (bottom of the core extrapolated to ≈ 1935 YBP). Each 1 cm sample averages ≈ 26 years of sedimentation (top-most samples ≈ 46 years, middle samples ≈ 19 years, and bottom-most samples ≈ 24 years).
**Diatom enumeration**

I digested the ca. 1 g wet mass of lake sediments from each 1 cm sub-sample designated for diatom analyses following the guidelines of Battarbee (1986). Wet samples were first washed with 10% HCl and rinsed with deionized water (18 megohm-cm resistivity) to remove any carbonates. Then, they were digested with 30% H₂O₂ to remove organic matter and given a final rinse with deionized water. At this point, only silicates remained suspended in deionized water. To avoid damaging any frustules, all suspended samples were allowed to settle via gravity for 24 hours after each washing and rinsing sequence in lieu of centrifuging. No sieving was necessary because the sediments were devoid of coarse-grained (> 0.5 mm) organic and inorganic debris. Also, separation of diatoms via suspension in heavy liquids was not necessary. Washed samples were transferred to glass cover slips and one drop of ammonium hydroxide was added to prevent clumping of diatoms. The samples were allowed to evaporate before permanently mounted on glass slides with Naphrax (refractive index = 1.65).

Diatom species were identified by use of 1000X phase-contrast microscopy with a Zeiss Axioskop microscope following the taxonomy of Patrick and Reimer (1966, 1975), Williams and Round (1987), and Wehr and Sheath (2003). All species taxonomy and names were updated and verified with the Integrated Taxonomic Information System database (ITIS) and the North American Diatom Ecological database with information current as of October 2008. At least 600 frustules per 1 cm sample were counted to determine the relative abundance of each species. Also, broken frustules were ignored unless the broken valves had enough material (usually > 50% of the valve remaining) to allow proper species identification with the dichotomous key. In total, 45,711 frustules from a total of 80 species from 25 genera were identified and enumerated.
Statistical analyses

I analyzed the diatom relative abundance data in three steps. Before analysis, any diatom species that composed < 0.5% of the relative abundance of any depth profile was removed from the matrix. This process reduced the original 80 species to 78 species used for further analyses. For the first step, the relative abundance matrix was normalized using the arcsine-square root transformation (Gotelli and Ellison 2004). Second, to reduce the dimensionality of the diatom community and to identify important individual species, I performed principal components analysis (PCA) on the variance-covariance matrix of the normalized diatom relative abundance data over the 75 sub-samples. PCA is appropriate for the multicollinearity often found in time series and relative abundance data (Gotelli and Ellison 2004). I used the variance-covariance matrix because it preserves random noise in the variables, it preserves the sums of the variances, and PCA assumes that large variances in the matrix have large dynamics in PCA space. All of these aspects are important when identifying data noise and true trends, especially within newly created multivariate PCA variables (Johnson 1998). Each principal component (PC) point along a PCA axis is a factored representation of the entire diatom community at that specific point. The major species loadings on each PCA axis indicate the ecological characteristics of the community at each step. Third, I analyzed the newly created PCA axes with SiZer (significance of the zero crossings of the derivative). SiZer is a statistical technique that applies a series of smoothing functions based on bandwidths around the data to statistically analyze which data in a matrix or series are true trends and which data are noise or are attributable to sampling variation (Zhang and Marron 2005, Rondonotti et al. 2007). Essentially, SiZer identifies the true modality of the data by applying derivatives; where there is a significant zero crossing of the derivative ($\alpha = 0.05$ around confidence interval 0), there is a significant shift in the composition of the data.
structure that is independent of noise or sampling variability. SiZer accomplishes this by
accounting for both the overall linear trend of the data as well as alternating oscillations along
this trend. SiZer is a freeware application that is distributed from www.wagner.com.

I also applied SiZer to other data analyzed in my study, including the tree ring data
(Grissino-Mayer 1995, 1996), solar activity data (Reimer et al. 2004), the percent organic matter
in the sediments determined from LOI, and the nine diatom species with the greatest loadings
along PC1. All analyses were performed at \( \alpha = 0.05 \). Once the SiZer analyses were completed,
I visually compared regions of significant zero crossing for correspondence in pattern and timing
among all of the variables measured.

As a more rigorous test of correspondence, I also used cross-correlation analysis to
analyze overlapping patterns in diatom PC1, tree ring (Grissino-Mayer 1995, 1996), and solar
activity (Reimer et al. 2004) data. Before applying cross-correlation, I had to perform
preparatory procedures because each data set had different time steps and total time ranges. The
diatom and solar intensity data both superficially originated at AD 1950 (0 YBP) due to the
radiocarbon method, and the tree rings ended in real-time AD 1992. First, I deleted tree ring data
from AD 1992-1951 to match the start dates of diatom PC1 and solar intensity at AD 1950 (0
YBP). Then, I truncated all data series at \( \approx 1935 \) YBP because the sediment core ended at this
date. Also, my diatom data were in \( \approx 26 \)-year steps, the solar data were in 5-year steps, and the
tree ring data were in annual steps. Therefore, data interpolation and/or deletion was necessary
to align the series. To ensure that manipulation would not significantly alter data trends, I
performed autocorrelation analysis (Appendix 1). Then, to reduce simultaneously the length of
time (interpolate) between time steps in diatom PC1 and sun data, and increase the length of time
(delete-smooth) between each step in the tree ring and speleothem data, I smoothed each data
series with a SiZer log_{10}(h) = 0.986 bandwidth. This bandwidth is mathematically similar to a 20-year moving average spline (Appendix 1). This method transformed each data series into 400 discrete time steps, each step at 4.8375 years, which allowed for alignment in cross-correlation analysis. All cross-correlations were run at 0-100 year lags at $\alpha = 0.05$.

RESULTS

Paleo-precipitation and solar activity

The paleo-precipitation data from tree rings (Grissino-Mayer 1995, 1996) are presented in Fig. 2. Over the course of the last two millennia, inferred precipitation (from Grissino-Mayer 1995, 1996) has fluctuated by up to 31 cm, with a maximum yearly rainfall of 57.4 cm and a minimum yearly rainfall of 26.4 cm. The average from 1935 YBP to present is 37.1 cm. Distinct peaks in greater than average precipitation occurred near present day, 200, 800, 900, and 1400 YBP. Conversely, distinct nadirs in precipitation occurred near 400, 600, 1200, 1600, and 1900 YBP.

My SiZer analyses on the data (only 1935 YBP to present) from Grissino-Mayer (1995, 1996) indicated six significant changes in the precipitation regime along the continuum between the family of bandwidths in the log_{10}(h) = 1.56 to 2.37 spectra (Fig. 2). A significant drying trend originated at 1670 YBP and ended at 1440 YBP. After this dry spell, a period with significantly more precipitation spanned 1440-1235 YBP. These near-regular cycles of alternating dry-wet periods remained throughout the length of the time series, with significant dry periods spanning 1235-935 YBP and 610-176 YBP, and significant wet periods spanning 935-610 YBP and 176 YBP-present. The average length of each dry period lasted 321 years and the average of each wet period, when including the current one spanning 204 YBP to present,
FIG 2. Inferred precipitation of northern New Mexico generated by Grissino-Mayer (1995, 1995). The series has been truncated to show only 1935-0 YBP (0 YBP = AD 1950). The original data are in the smaller panel and are represented by the black line. The 20-year smooth of those data are represented with the white line drawn through the black line. The large panel shows SiZer bandwidths of the tree ring data in the log_{10}(h) = 1.56 to 2.37 spectra. The dashed line is the linear regression of the original tree ring data, which is an important component in calculating zero crossings of the derivative. The open circles indicate points of significant change based on zero crossings of the derivative.
lasted 235 years. The average of all wet and dry cycles combined is 278 years. When the most recent 204 year wet oscillation is removed, the average wet cycle is 248 years and the average of all wet and dry cycles is 265 years.

The inferred paleo-solar activity data from Reimer et al. (2004) are reported in Fig. 3 and also show variation through time. There are noticeable peaks in solar activity (negative $^{14}$C delta values) near present day, 800, 1000, and 1400 YBP. Conversely, there are visible nadirs in solar activity (positive $^{14}$C delta values) near 250, 425, and 620 YBP. Cycles in solar activity appear to follow both 200 and 400-year oscillations. Further information on harmonic analyses of the solar cycles is reported in Yu and Ito (1999).

My SiZer analyses on the solar activity data (only 1935 YBP to present) from Reimer et al. (2004) showed five significant transitions in the solar regime along the continuum between the family of bandwidths in the $\log_{10}(h) = 1.68$ to 2.37 spectra (Fig. 3). A significant increase in solar activity originated at 1650 YBP and ended at 1290 YBP. After this cycle, a brief period of significantly reduced solar activity spanned 1290-1150 YBP. Continuing cycles of alternating increased-decreased solar activity remained throughout the length of the time series, with significant increases in solar activity spanning 1150-665 YBP and 148 YBP to present. These two periods of increased solar activity enveloped a period of a significant decrease in solar activity spanning 665-148 YBP. The average length of each active period, when including the current one spanning 148 YBP to present, lasted 331 years and the average of each less active period lasted 329 years. The average of all cycles combined is 330 years. When the most recent active oscillation from 148 YBP to present is removed, the average active cycle lasted 439 years and the average of all cycles is 376 years.
FIG. 3. Inferred solar intensity data generated by Reimer et al. (2004). The series has been truncated to show only 1935-0 YBP (0 YBP = AD 1950). Decreasing delta values indicate increasing solar intensity. The line with opaque circles is the original data of Reimer et al. (2004). The dashed line is the linear regression of the solar intensity data, which is an important component in calculating zero crossings of the derivative. The other solid lines are the SiZer family of bandwidths in the $\log_{10}(h) = 1.68$ to 2.37 spectra. The open circles indicate points of significant change based on zero crossings of the derivative.
Sediment core characteristics

The chronosequence of the Santa Fe Lake core was established from six $^{14}$C analyses. Each carbon date was the median calibrated age using a 2-sigma calibrated age range (INTCAL 98, Stuvier et al. 1998). The dating sequence was in chronological order. The top sample of the core was $^{14}$C dated as post-present day (present day = AD 1950; 0 YBP ± 40 years) and, thus, was considered as AD 1950 (0 YBP) to maintain consistency with the other 5 $^{14}$C dates. The bottom sample of the core dated to 1902 YBP ± 40 years. The sedimentation rate of Santa Fe Lake was variable, ranging between 0.33 cm per year (1 cm ≈ 46 years) at the top of the core to 0.63 cm per year (1 cm ≈ 24 years) at the bottom. An age-depth profile of sediment, $^{14}$C age, and $^{14}$C errors are presented in Fig. 4. Each age-depth profile point along the continuum was estimated from a cubic spline regression of the six $^{14}$C dates.

The Santa Fe Lake core was dominated by a nearly homogenous slurry of gyttja at all depths from the surface to the bottom. The bulk organic content of the core (Fig. 5) was mostly consistent throughout the core, with the exceptions from near 400 YBP to the present that ranged from a low of 24.2% (LOI) to a high of 46.3% (LOI). SiZer indicated three significant transitions in the organic matter content between the family of bandwidths in the log_{10}(h) = 2.02 to 2.37 spectra (Fig. 5). At ≈ 864 YBP the organic content transitioned to a significantly higher proportion than the previous running trend. Conversely, at ≈ 721 YBP the sediments changed to having a lower organic content until ≈ 128 YBP when sediments then increased to a maximum value of 46.3% at 0 YBP.
FIG. 4. Age-depth profile for the Santa Fe Lake sediment core based on $^{14}$C analysis. The points were best-fit with a cubic spline regression. Error bars are age errors generated from fraction of modern $^{14}$C errors.
FIG. 5. Organic content-depth profile for the Santa Fe Lake core determined by loss on ignition (LOI). The line with opaque circles is the original % organic matter data. The dashed line is the linear regression of % organic matter, which is an important component in calculating zero crossings of the derivative. The other solid lines are the SiZer family of bandwidths in the log_{10}(h) = 2.02 to 2.37 spectra. The open circles indicate points of significant change based on zero crossings of the derivative.
Diatom community shifts

The diatom community contained 80 species from 32 genera (Appendix 2) and was highly plastic throughout the depths of the Santa Fe Lake core. PCA extracted two main axes for further analyses, which cumulatively accounted for ca. 37% of the total community variance; PC1 accounted for 24.0% of the variance within the diatom community (Fig. 6), and PC2 accounted for 13.0% of the variance (Fig. 7). PC3 accounted for only 8.3% of the variance and was omitted from further analyses.

Seven diatom species were strongly associated with PC1 (communalities > 0.50; Table 1, Fig. 8). Species with the most positive loadings along PC1 included *Aulacoseira distans* var. *alpigena*, *Cyclotella meneghiniana*, *Navicula radiosa* var. *radiosa*, and *Synedra tenera* (syn. *Fragilaria tenera*). Ecologically, *A. distans* var. *alpigena* and *N. radiosa* var. *radiosa* are species that prefer circumneutral water but can tolerate a variety of pH levels (Hustedt 1939, Patrick and Reimer 1966, 1975, Charles 1984, 1985). Additionally, *A. distans* var. *alpigena* is a common indicator of turbid water columns (Patrick and Reimer 1966, 1975, Sherman et al. 1998, Licursi et al. 2006). *C. meneghiniana* is a euryhaline species that is often used as an indicator of increases in water salinity but can also tolerate a variety of pH levels (Gasse 1987, Laird et al. 1998). *S. tenera* is an acidophilic species that prefers water pH below 7 (Hustedt 1939, Patrick and Reimer 1966, 1975, Lynch et al. 1988, Charles 1984, 1985). Conversely, PC1 was negatively loaded by *Achnanthes lanceolata* var. *lanceolata* (syn. *Planothidium lanceolata*), *Staurosira construens* var. *venter*, and *Staurosirella pinnata* var. *pinnata*. These three species are small benthic taxa that are alkaliphilic, preferring water pH above 7 (Hustedt 1939, Patrick and Reimer 1966, 1975, Charles 1984, 1985, Laing et al. 1999). Therefore, as PC1 scores become more positive, the relative abundances of *A. distans* var. *alpigena*, *C. meneghiniana*, *N.
FIG. 6. Diatom PC1-depth profile for the Santa Fe Lake core. The line with opaque circles is the original diatom PC1 data. The dashed line is the linear regression of the diatom PC1 data, which is an important component in calculating zero crossings of the derivative. The other solid lines are the SiZer family of bandwidths in the $\log_{10}(h) = 1.91$ to 2.37 spectra. The open circles indicate points of significant change based on zero crossings of the derivative.
FIG. 7. Diatom PC2-depth profile for the Santa Fe Lake core. The line with opaque circles is the original diatom PC2 data. The dashed line is the linear regression of the diatom PC2 data, which is an important component in calculating zero crossings of the derivative. The other solid lines are the SiZer family of bandwidths in the log_{10}(h) = 1.91 to 2.37 spectra. The open circles indicate points of significant change based on zero crossings of the derivative.
TABLE 1. The nine diatom species with the greatest individual loadings (cutoff was > ± 0.030 because these species loadings had communalities > 0.50) on the first two principal component analyses axes.

<table>
<thead>
<tr>
<th>Taxon</th>
<th>PC1 loadings</th>
<th>PC2 loadings</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Aulacoseira distans</em> var. <em>alpigena</em>&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>0.051</td>
<td>0.012</td>
</tr>
<tr>
<td><em>Cyclotella meneghiniana</em>&lt;sup&gt;1,3&lt;/sup&gt;</td>
<td>0.072</td>
<td>0.025</td>
</tr>
<tr>
<td><em>Navicula pupula</em> var. <em>pupula</em>&lt;sup&gt;1&lt;/sup&gt;</td>
<td>-0.009</td>
<td>-0.045</td>
</tr>
<tr>
<td><em>N. radiosa</em> var. <em>radiosa</em>&lt;sup&gt;1&lt;/sup&gt;</td>
<td>0.063</td>
<td>-0.004</td>
</tr>
<tr>
<td><em>Pinnularia abaujensis</em> var. <em>subundulata</em>&lt;sup&gt;4&lt;/sup&gt;</td>
<td>-0.011</td>
<td>-0.056</td>
</tr>
<tr>
<td><em>Synedra tenera</em> (syn. <em>Fragilaria tenera</em>)&lt;sup&gt;4&lt;/sup&gt;</td>
<td>0.044</td>
<td>0.009</td>
</tr>
<tr>
<td><em>Achnanthes lanceolata</em> var. <em>lanceolata</em>&lt;sup&gt;5&lt;/sup&gt;</td>
<td>-0.045</td>
<td>0.014</td>
</tr>
<tr>
<td><em>Staurosira construens</em> var. <em>venter</em>&lt;sup&gt;5&lt;/sup&gt;</td>
<td>-0.098</td>
<td>0.026</td>
</tr>
<tr>
<td><em>Staurosirella pinnata</em> var. <em>pinnata</em>&lt;sup&gt;5&lt;/sup&gt;</td>
<td>-0.036</td>
<td>-0.017</td>
</tr>
</tbody>
</table>

Notes: <sup>1</sup>Circumneutral, acid-tolerant species; <sup>2</sup>turbidity-tolerant species; <sup>3</sup>euryhaline, hyposaline species; <sup>4</sup>acidophilic species; <sup>5</sup>alkaliphilic species (see text for more details)
FIG. 8. Relative abundance-depth profiles for the nine species of diatoms with the most predominant loadings from PCA within the Santa Fe Lake core. The dashed lines are the linear regressions of the diatom relative abundance data, which are important components in calculating zero crossings of the derivative. The other solid lines are the SiZer bandwidths (see text for spectra). The open circles indicate points of significant change based on zero crossings of the derivative. Note the different scale used for *S. construens* var. *venter*, which has the units offset on the right axis.
radiosa var. radiosa, and S. tenera increase, which suggests the lake water has become more acidic, turbid, and saline; likewise, their decline is indicative of waters becoming less turbid, saline, and acidic (PC1 scores become more negative). As the PC1 scores become more negative, the relative abundances of A. lanceolata var. lanceolata, S. construens var. venter, and S. pinnata var. pinnata increase, which suggest the lake water has become more alkaline; likewise their decline is indicative of reduced alkalinity (as PC1 scores become more positive). Ultimately, it appears that PC1, as a whole, is capturing diatom community variance associated with changes in water chemistry and turbidity.

SiZer indicated that there were four significant changes in the diatom community along this continuum between the family of bandwidths in the $\log_{10}(h) = 1.91$ to 2.37 spectra. Between $\approx 1439$-1000 YBP, diatoms significantly changed to more positive PCA scores (from ca. -0.4 to ca. +1.3). After this, between $\approx 1000$-585 YBP, the diatoms significantly changed to more negative PCA scores (ca. +1.3 to ca. -0.5). Between $\approx 585$-213 YBP, diatoms again significantly shifted towards more positive PCA scores (ca. -0.5 to ca. +2.5). Subsequently, between $\approx 213$ YBP and present day, the PCA scores become significantly less positive (ca. +2.5 to ca. +0.4) for the remainder of the series. The average length of each period of increasingly positive PCA scores is 404 years. The average length of each period of increasingly negative PCA scores, when including the current one spanning 213 YBP to present, is 314 years. The average of all negative and positive cycles is 359 years. When the most recent negative oscillation from 213 YBP to present is removed, the average of all negative and positive cycles averaged 408 years.

Only three diatom species were strongly associated with the PC2 axis. Navicula pupula var. pupula (syn. Sellaphora pupula) loaded positively along the axis and A. lanceolata var. lanceolata (also associated with PC1) and Pinnularia abajensis var. subundulata loaded
negatively along the PC2 axis (Table 1 and Fig. 8). Ecologically, *N. pupula* var. *pupula* prefers circumneutral water and *P. abaujensis* var. *subundulata* is an acidophil that prefers water below pH 7 (Hustedt 1939, Patrick and Reimer 1966, 1975, Charles 1984, 1985). Therefore, as PC2 scores become more positive, the relative abundance of *N. pupula* var. *pupula* increases; as PC2 scores become more negative, the relative abundances of *A. lanceolata* var. *lanceolata* and *Pinnularia abaujensis* var. *subundulata* decrease. PC2 is not as clearly associated with water chemistry as PC1, but it does suggest linkages with overall levels of primary productivity in the lake. Organic matter (Fig. 5), which is a coarse surrogate for productivity, generally resembles the patterns in PC2 (Figs. 7 and 9). Nevertheless, because PC2 only explains 13.0% of the communal variance and only has three diatom species significantly loaded on PC2, I omitted PC2 from any subsequent ecological interpretations.

The seven diatom species with the highest PCA loadings along PC1 were highly plastic in their relative abundances through time (Fig. 8). These seven species demonstrated significant (via SiZer) changes in relative abundances throughout the time series. *S. construens* var. *venter* consistently had the highest relative abundances (up to ca. 76%) of the community. *A. lanceolata* var. *lanceolata* had the second greatest relative abundance peak (ca. 15%) and *C. meneghiniana* had the third greatest relative abundance peak (ca. 14%). The other species demonstrated lower relative abundance peaks throughout the length of the core.

The relative abundance of *S. construens* var. *venter* (alkaliphilic) had four significant changes along the long-term time series. SiZer (bandwidths in the log$_{10}$[h] = 1.79 to 2.60 spectra) indicated that the relative abundance of *S. construens* var. *venter* significantly increased between $\approx 1065-571$ YBP and from $\approx 179$ YBP to present. Conversely, between these
FIG. 9. Relationships between Santa Fe Lake % organic matter (same as Fig. 5) and diatom PC2 (same as Fig. 7). The vertical dashed line shows corresponding bifurcations in the organic matter and diatoms.
increasing intervals, the relative abundances significantly decreased from ≈ 1415-1065 YBP and ≈ 571-179 YBP.

*A. lanceolata* var. *lanceolata* (alkaliphilic) had one significant change in its relative abundance over time. The lone significant change (SiZer bandwidths in the log_{10}[h] = 2.14 to 2.60 spectra) was at ≈ 1556 YBP when the relative abundances significantly decreased for the remainder of the time series.

The relative abundance of *C. meneghiniana* (euryhaline) had four significant changes in relative abundance over time. SiZer (bandwidths in the log_{10}[h] = 1.79 to 2.60 spectra) indicated that the relative abundance of *C. meneghiniana* increased between ≈ 1414-1083 YBP and ≈ 597-197 YBP. Conversely, between these increasing intervals, the relative abundances significantly decreased between ≈ 1083-597 YBP and from ≈ 197 YBP to present.

The remaining four of the seven most dominant diatoms along PC1 had lower relative abundances and fewer significant transitions in their relative abundances through time. *A. distans* var. *alpigena* (circumneutral, turbid) peaked in its relative abundance between ≈ 461-133 YBP (SiZer bandwidths in the log_{10}[h] = 2.14 to 2.60 spectra). *N. radiosa* var. *radiosa* was bimodal in its relative abundance peaks, with maxima between ≈ 1240-1100 YBP and from ≈ 547 YBP to present. *Synedra tenera* (syn. *Fragilaria tenera*; acidophilic) was also similarly bimodal in its distribution like *N. radiosa* var. *radiosa*, with bimodal peaks between (SiZer bandwidths in the log_{10}[h] = 1.79 to 2.37 spectra) ≈ 1166-1021 YBP and ≈ 584-139 YBP. Finally, *S. pinnata* var. *pinnata* was unimodal in its distribution, with a relative abundance peak (SiZer bandwidths in the log_{10}[h] = 2.14 to 2.71 spectra) between ≈ 1618-1002 YBP.
Cross-correlations

In addition to using SiZer to identify significant transitions in the diatom community through time, I used cross-correlation analysis to test the relationships between calibrated environmental phenomena (from tree rings and solar activity) and diatom PC1. For my first analyses, I tested the relationship between inferred drought from the tree ring data of Grissino-Mayer (1995, 1996) and the diatom PC1 axis (Fig. 10). The correlation at zero lag is significant ($r = -0.15$, $p < 0.002$). The strongest correlations were at -63 and +15 years ($r = -0.17$, $p < 0.001$, both respectively). These correlations imply that as inferred precipitation increases, diatom PC1 becomes more negative. For my second analysis, I tested the relationship between inferred sun activity from the $^{14}$C data of Reimer et al. (2004) and the diatom PC1 axis (Fig 11). The correlation at zero lag is highly significant ($r = 0.78$, $p < 0.001$). The strongest correlation was at -24 years ($r = 0.79$, $p < 0.001$). Both of these correlations offer evidence that solar activity has a near-zero lag, possibly imparting direct modulation on the diatom community in Santa Fe Lake; as solar intensity increases, diatom PC1 becomes more negative. As a final test, I tested the relationship between inferred precipitation (tree rings) and solar activity (Fig. 12). The correlation at zero lag was significant and also the strongest correlation in the comparison ($r = -0.15$, $p < 0.001$). This correlation suggests that solar intensity is related to inferred precipitation; as solar intensity increases, precipitation concomitantly increases with zero lag.

DISCUSSION

The main objective of this study was to generate an alternative paleo-drought record for New Mexico using diatoms in lieu of other proxy methods. Two other proxy methods previously used from New Mexico (tree rings [Grissino-Mayer 1995, 1996] and speleothems [Polyak and
Fig. 11. Cross-correlation between the solar intensity data from Reimer et al. (2004) and diatom PC1.

Zero lag: $r = 0.78$, $p < 0.001$
Maximum correlation: -24 years, $r = 0.79$, $p < 0.001$
Fig. 12. Cross-correlation between the solar intensity data from Reimer et al. (2004) and the tree ring data from Grissino-Mayer (1995, 1996).
Asmerom 2001, Rasmussen et al. 2006]) had some notable differences (cf. Betancourt et al. 2002). Mainly, they showed asynchrony in precipitation patterns, and their interpretations of the near modern analog came to opposite conclusions. Also, the tree ring record suggested that the last 200 years have been a period of relative wetness, whereas the speleothem record suggested the same period has been relatively dry compared to the long-term trend. Furthermore, recent research has demonstrated that alternations in solar intensity have strong concordance with drought frequency (Yu and Ito 1999, Hodell et al. 2001, Asmerom et al. 2007). However, various interpretations of solar intensity also appear to have conflicting results about solar oscillations and drought cycles. Specifically, depending on the region studied, solar oscillations can concomitantly cause drought in one region but increase precipitation in another (Asmerom et al. 2007). My study further examines patterns of solar-induced drought in New Mexico.

My results suggest that Santa Fe Lake diatoms changed in association with inferred fluctuations in lake water pH, turbidity, and salinity. My data agree with the tree ring record (Grissino-Mayer 1995, 1996), which corroborates the asynchrony between tree rings and speleothems suggested by Betancourt et al. (2002). Furthermore, this corroboration indicates that the near modern climate analog of northern New Mexico has demonstrated relative wetness over the most recent 200 years. Also, patterns of decreased solar activity may have contributed to historical droughts in the region. Because changes in diatom community structure closely matched changes in solar activity and tree ring data, I deduced that solar activity possibly had an influence on precipitation and lake conditions in northern New Mexico.

Changes in indicator species of turbidity and salinity from Santa Fe Lake diatoms are strong foundations to develop an inferred drought cycle, but there are other biogeochemical interactions that affect pH that need to be considered. Specifically, while it is traditionally
regarded that increases in lake level often intensify acidity, and reductions in lake level often increase alkalinity (Wetzel 2001), I argue that these biogeochemical interactions operate differently in the drought regime of Santa Fe Lake. Expressly, because Santa Fe Lake is a granite-bottomed and acid sensitive lake (Lynch et al. 1988), I propose that drought-induced acidification (Arnott et al. 2001, Faulkenham et al. 2003) was a substantial process that influenced diatom community structure. When the changes in diatom community structure are compared to an existing drought record in northern New Mexico (Grissino-Mayer 1995, 1996), there is considerable evidence of coincidental drought-induced oscillations in the diatom-inferred acid-alkaline profile, demonstrating that drought-induced acidification could be an important modulator in Santa Fe Lake.

The insights gained from using SiZer analyses of the diatom community permitted statistical identification of specific points in time when the community significantly changed from one dominant profile to another. Specifically, the use of SiZer elucidated when the major indicator diatoms of Santa Fe Lake statistically shifted from drought indicator species to non-drought indicator species, and vice versa. Then, these diatom shift points could be visually compared to extraneous forces, such as precipitation and solar intensity to infer concordant bifurcations. If precipitation and solar intensity switch-points were within close proximity of diatom bifurcations, then there would be evidence supporting drought-induced diatom changes.

As an outline of my discussion, I examine the concordance of community-level diatom shifts with a previously calibrated paleo-climate record of New Mexico, propose lake-induced water condition mechanisms that caused changes in the representative, indicator diatom taxa, and discuss possibilities for the disagreements associated with the effects of solar activity on
precipitation. My results may help resolve differing interpretations of the near modern climate analog and potential impacts of solar forcing on the climate of northern New Mexico.

**Corresponding community-level diatom changes with regional climate**

Before interpreting the autecology of individual indicator diatom species in Santa Fe Lake, it is important to identify community-level shifts that align with previously calibrated drought cycles in New Mexico. While diatoms can be calibrated as their own independent surrogates of drought (Fritz et al. 1993, Laird et al. 1998, Cohen 2003), it was essential for my study to correlate measurable community-level diatom changes to previously calibrated drought records because of my objective to infer the effects of solar modulation on drought regimes. By supposing that solar cycles modulate precipitation and that precipitation influences lake water condition, which in turn shapes the diatom community, then it must be true that both the precipitation record and the diatom community correlate independently with solar activity. This linkage would imply such a transitive relationship between solar intensity and diatoms.

The entirety of my community-level argument is based on interpretations of diatom PC1, which, as a newly derived single variable, represents a factored interpretation of the prevailing community characteristics. Specifically, as PC1 scores become more positive, the relative abundances of diatom indicator species of acidic pH, increased turbidity, and increased salinity become greater (Figs. 6 and 8). Conversely, as PC1 scores become more negative, indicator species of increased alkalinity become more abundant. Therefore, based on autecology interpretations from the literature, as PC1 becomes more positive, they are indicative of drought conditions; as PC1 scores become more negative, they are indicative of periods with increased precipitation (Figs. 6, 8 and 13).
FIG. 13. Relationships between the tree ring data of Grissino-Mayer (1995, 1996) (same as Fig. 1) and diatom PC1 (same as Fig. 5). The vertical dashed line shows corresponding bifurcations in the tree rings and diatoms. Note that the yearly precipitation scale has been inverted to aid in visual correspondence with diatom PC1.
The tree ring record of precipitation (Grissino-Mayer 1995, 1996) is significantly inverse cross-correlated with diatom PC1, showing that as precipitation increases, diatom PC1 decreases (wetter) (Fig. 10). While there is some lag in the cross-correlations between tree rings and diatom PC1, this may be due to differences in dating methods. The maximum error rate in my \(^{14}\)C radio-dates is ±40 years. When considering the wavelength between the maximum correlations is 78 years (lag at -15 and 63 years, \(r = -0.17, p < 0.001\), both respectively) and the \(^{14}\)C error rate ±40 years, there is ample support suggesting the diatoms of Santa Fe Lake and the tree rings of Grissino-Mayer (1995, 1996) captured the same precipitation variance within a ±40 year window (best case scenario no lag; worst case scenario 103 years lag). Nevertheless, there is strong statistical evidence that the inferred precipitation regime is correlated to the plasticity of diatom assemblage from Santa Fe Lake.

In addition to the corroboration between diatom PC1 and tree ring records of inferred drought, there is also strong visual correspondence between these profiles (Fig. 13). SiZer indicated that the average wavelength for wet-dry intervals in the tree ring record is 278 years and the average wavelength between PC1 score positive-negative oscillations was 408 years. The difference between wavelengths is likely from differential sensitivity to precipitation, with tree rings presumably being more sensitive, and differences in their autocorrelation structure, with diatoms having longer lag (see Appendix 1 for more information). However, these two records generally have visually corresponding peaks and nadirs in their trajectory, as well as similarly corresponding significant zero crossings, despite having different average wavelengths (Fig. 13). Corresponding significant zero crossings imply both proxy series responded concomitantly to major changes in exogenous forces; e.g. despite each proxy having differential sensitivity, they both captured the same major (as opposed to lesser) precipitation bifurcations at
nearly the same times. Periods of increasing precipitation had matching periods when PC1 scores became more negative and vice versa. There were concordant significant transitions in both the tree ring and PC1 records generally near \( \approx 1400, \approx 1000, \approx 600, \) and \( \approx 200 \) YBP, suggesting that significant changes in precipitation corresponded with significant changes in the diatom community at near 400-year intervals. As a whole, the inferred precipitation regime of Grissino-Mayer (1995, 1996) shows good concordance with diatom PC1. From this combination of tree ring data and diatom PC1, there is substantial evidence suggesting that the nearly modern climate analog of northern New Mexico has been wetter than previous times in the series, which is in contrast to interpretations of southern New Mexico (Polyak and Asmerom 2001, Rasmussen et al. 2007, Asmerom et al. 2007).

Furthermore, the solar activity data from Reimer et al. (2004) is also significantly cross-correlated with diatom PC1 (Fig. 11); specifically, the correlation at zero lag is highly significant \( (r = 0.78, p < 0.001) \). It is important to note the solar \(^{14}\)C data also superficially started at AD 1950; this likely had some effect in the near-zero lag correlation. It is also possible that the maximum correlation (lag at -24 years, \( r = 0.79, p < 0.001 \)) may be due to error rates of the radiocarbon method. Nonetheless, there is strong statistical concordance between solar activity and the drought-indicating diatom species in Santa Fe Lake with no lag.

Also, the cycles of oscillating solar intensity have strong visual concordance in peaks, nadirs, and significant zero crossings with diatom PC1 (Fig. 14). Periods of decreasing solar activity (more positive delta \(^{14}\)C values) had matching periods when PC1 scores became more positive (drier), and vice versa. The linkage between decreased solar activity and increased droughts has previously been established in other regions (Yu and Ito 1999, Neff et al. 2001, Fleitmann et al. 2003, Wang et al. 2005), with some notable exceptions elsewhere (Hodell et al.
FIG. 14. Relationships between the solar intensity data of Reimer et al. (2004) (same as Fig. 3) and diatom PC1 (same as Fig. 6). The vertical dashed line shows corresponding bifurcations in the solar intensity and diatoms.
Additionally, the literature on solar activity has demonstrated both ca. 200 and ca. 400-year oscillations that affect climate (Cook et al. 1996, Yu and Ito 1999, Hodell et al. 2001). While the average wavelength of significant solar oscillations determined from my SiZer analyses was 376 years (Fig. 3), there are marked non-significant oscillations of near 200 years in the data (also, autocorrelation analysis [Appendix 1] indicated a 450 year dependency cycle, which is similar to the 440 year solar cycle widely reported in the literature [e.g. Asmerom et al. 2007]). SiZer determined that diatom PC1 had an average wavelength of 408 years, but smaller and non-significant oscillations were also visually present (Fig. 7). These corresponding 200-year transitions were statistically captured through the very strong cross-correlation between solar activity and diatom PC1 (Fig. 11), but were not visually aligned within the SiZer crossings (Fig. 11). However, the majority of the SiZer-determined significant solar cycles visually corresponded with significant diatom cycles quite well (Fig. 12). Corresponding significant zero crossings imply both proxy series responded concomitantly to major changes in exogenous forces; e.g. changes in sun intensity simultaneously altered atmospheric $^{14}$C production and precipitation regimes during overlapping ca. 400-year intervals. Furthermore, regardless of points of significant zero crossing, the two series have marked visual correspondence, particularly with respect to peaks and nadirs. As a whole, through visual correspondence and statistical calculations, the record of decreased solar activity and diatom PC1 inferred cycles of drought show remarkable concordance.

As an additional test of the effect of solar activity on the climate of northern New Mexico, I compared the solar activity record of Reimer et al. (2004) to the tree ring record of Grissino-Mayer (1995, 1996). This test was essential to validate the transitive relationships between solar intensity, precipitation, and diatom dynamics. There is a significant inverse cross-
correlation between the tree rings and solar activity (zero lag cross-correlation $r = -0.15$, $p < 0.001$, Fig. 12). The strongest correlation is at the zero lag, suggesting that changes in solar activity possibly affected precipitation at less than decadal time scales. This general interpretation is consistent with solar-induced drought cycles reported elsewhere (Yu and Ito 1999, Neff et al. 2001, Fleitmann et al. 2003, Wang et al. 2005).

SiZer bandwidths further showed visual correspondence between solar intensity and tree rings with respect to peaks, nadirs, and significant zero crossings (Fig. 15). Periods of decreased solar activity (positive $^{14}$C delta values) had matching periods of reduced inferred precipitation, and vice versa (Fig. 15). Similarly to the differences found between the solar record and diatom PC1, both the tree ring record and solar record have ca. 200 and ca. 400-year cycles that did not always have overlapping points of significant zero crossing. However, the overall strength between these two series was demonstrated through the significant cross-correlation. Ignoring the points of significant zero crossing, the two series have strong visual correspondence, particularly with respect to peaks and nadirs. Also, the current trajectory of increasing solar activity from 148 YBP towards present match the nearly modern analog of Grissino-Mayer (1995, 1996) suggesting a period of relative wetness. Ultimately, there is circumstantial evidence that solar activity may have modulated the precipitation of northern New Mexico and, therefore, established a potential link between solar modulation and diatom dynamics.

From the information about tree rings, and solar activity I have presented thus far, there are multiple layers of substantive evidence that statistically validate that the changes in the Santa Fe Lake diatom community dynamics closely tracked changes in the regional New Mexico climate. Next, I propose why these shifts in diatom community represent the regional precipitation regime.
FIG. 15. Relationships between the tree ring data from Grissino-Mayer (1995, 1996) (same as Fig. 2) and the solar intensity data of Reimer et al. (2004) (same as Fig. 3). The vertical dashed line shows corresponding bifurcations in the tree rings and solar intensity. Note that the yearly precipitation scale has been inverted to aid in visual correspondence with solar intensity.
Mechanisms of diatom drought response

Drought-induced changes in lakewater condition likely affected the diatoms in Santa Fe Lake in three ways. First, decreases in lake levels likely increased salinity. Euryhaline and hyposaline species of diatoms have been used to infer changes in salinity caused by changes in lake levels, which are surrogates of drought conditions (Cumming et al. 1995, Hodgson et al. 1996, Laird et al. 1998, Pienitz et al. 2000). Second, decreases in lake levels likely increased turbidity. As water levels fall, sediments often become increasingly exposed to wind-caused re-suspension (Nõges et al. 1999). Lake level-induced changes in turbidity have been shown to influence diatom community composition in lakes (Nõges et al. 1999, Heinsalu et al. 2008). Third, droughts have been shown to induce acidification in lakes (Arnott et al. 2001, Faulkenham et al. 2003), which in turn drastically alters the community diatom composition (Faulkenham et al. 2003). Diatoms have routinely been used as robust indicators of inferred changes in lake pH (Whitmore 1989, Weckström et al. 1997, Rosén et al. 2000).

One of the seven most important diatom species according to PC1 was *C. meneghiniana* (Table 1), which is a euryhaline/hyposaline indicator species (Laird et al. 1999). During prolonged periods of reduced precipitation (ca. 1400-1000 YBP and ca. 600-200 YBP), relative abundances of *C. meneghiniana* significantly increased (Fig. 8). This suggests that lake levels declined during this time, causing an increase in salinity. Conversely, when precipitation increased (ca. 1000-600 YBP and ca. 200 YBP to present), proportions of *C. meneghiniana* significantly decreased; this suggests an increase in lake level and, in turn, a decrease in salinity.

Another statistically important diatom in Santa Fe Lake was *A. distans* var. *alpigena* (Table 1). *Aulacoseira* is commonly described as a generic indicator of turbid (Sherman et al. 1998, Licursi et al. 2006) and turbulent (Lund 1954) water columns. Proportions of *A. distans*...
var. *alpigena* significantly increased during a period of reduced precipitation (ca. 400-200 YBP) (Fig. 8), suggesting lake levels decreased, which likely increased depth of turbulence and wave-induced re-suspension of sediments. The maximum depth of Santa Fe Lake during August AD 2007 was 7 m. Slight declines in lake levels could easily increase the amount of water turbulence that reaches the lake bottom, especially because turbulence (Richardson’s number) is proportional to depth; shallow water columns are less stable than deep ones (Wetzel 2001). The emergence of *A. distans* var. *alpigena* in the lake likely indicated a decrease in lake levels and, in turn, increased turbidity and turbulence.

While the emergence of *C. meneghiniana* and *A. distans* var. *alpigena* are linked to drought conditions, it is equally important to discuss species declines during drought conditions. Three statistically important (PC1, Table 1) species of alkaliphilic diatoms, *A. lanceolata* var. *lanceolata* (syn. *Planothidium lanceolata*), *S. construens* var. *venter*, and *S. pinnata* var. *pinnata*, significantly declined during various periods of inferred drought (ca. 1400-1000 YBP and ca. 600-200 YBP) (Fig. 8). Changes in alkalinity can come from a variety of mechanisms, but recent research has indicated that droughts can induce acidification in lake waters, particularly in highly acid-sensitive lakes with low calcium hardness and acid-neutralizing capacity (ANC) (Arnott et al. 2001, Faulkenham et al. 2003). The premise of this phenomenon is that lakes with low ANC, particularly with small basins, have the majority of their alkalinity produced internally through biological reduction of iron, sulfate, and nitrate (Schindler 1988). During lake level decline, the littoral zone becomes increasingly exposed to the atmosphere, preventing the reduction of iron, sulfur, and nitrogen (Schindler and Turner 1982, Schindler 1988, Arnott et al. 2001, Faulkenham et al. 2003). Once internal levels of reduced iron, sulfur, and nitrate decline, the lake’s ability to generate new alkalinity concomitantly declines (Schindler 1988, Ito et al.
Furthermore, the oxidative pathway of sulfur, ferrous iron, and ammonia (nitrification) releases hydrogen protons (Schlesinger 1997). These processes, in turn, can cause the water to become more acidic.

Santa Fe Lake is a candidate system for vulnerability to drought-induced acidification. The lake has a small basin (15.9 ha) completely underlain with Precambrian granite (Lynch et al. 1988). Moreover, the calcium hardness (6-27 mg/L) and ANC of the lake are low (5-10 mg/L), which classify the lake as highly acid sensitive (Lynch et al. 1988, Wetzel 2001) and suggest internal generation of alkalinity exceeds any terrestrial input of bedrock bicarbonate (Schindler 1988). New Mexico has gypsiferous soils, which likely provide aeolian inputs of sulfate to Santa Fe Lake (C.N. Dahm, personal communication). Also, precipitation in New Mexico has well-mixed, homogeneous levels of scavenged sulfate and nitrate (Popp et al. 1986). These imply that lake alkalinity may likely be largely generated from iron, sulfur, and nitrate reduction (Schindler 1988, Schlesinger 1997). Additionally, Santa Fe Lake has a shallow (< 1 m deep) and short littoral zone (extending ca. 1-5 m from shore) before steep drop-offs into the limnetic zone (J.Y.S. Hodgson, personal observation). If water levels dropped during drought conditions, increasingly exposing the littoral zone shelf to the atmosphere, it is likely that reduced forms of iron, sulfate, and nitrate would become oxidized, expediting their loss from the littoral zone. This would reduce alkalinity in the lake. Furthermore, any ferrous iron oxidation, sulfur oxidation, and nitrification in these exposed littoral zone areas would directly acidify the lake water if water movement from wave action, precipitation, and/or snow melt transported hydrogen protons into the water column (Schlesinger 1997, C.N. Dahm, personal communication). The combination of these factors suggest that Santa Fe Lake could experience intervals of drought-induced acidification, especially since the alkaliphilic diatoms of A.
lanceolata var. lanceolata, S. construens var. venter, and S. pinnata var. pinnata significantly declined during periods of drought.

As a confirmation of my supposition of drought-induced acidification in Santa Fe Lake, there should also be corresponding emergences of acidophilic and acid-tolerant diatom species during drought conditions. This corroborating evidence was present throughout the sedimentary record. Specifically, the relative abundance of the statistically important (PC1, Table 1) S. tenera (syn. F. tenera), which is an acidophilic species (Hustedt 1939, Patrick and Reimer 1966, 1975, Lynch et al. 1988, Charles 1984, 1985), significantly increased during two periods of drought (ca. 1200-1000 YBP and ca. 600-200 YBP) (Fig. 9). Additionally, the acid-tolerant species N. radiosa var. radiosa, which was also statistically important (PC1, Table 1), had similar peaks in relative abundance as S. tenera (syn. F. tenera) during drought conditions (ca. 1200-1000 YBP and ca. 600-200 YBP). The emergence of both of these species suggests that Santa Fe Lake became more acidic during droughts. Conversely, the significant declines of both of these species during non-drought periods suggest that the lake became more alkaline during periods of increased precipitation.

There are multiple forms of evidence, from the compensatory interactions of drought indicator diatom species (Fig. 8 and Table 1), suggesting that Santa Fe Lake has gone through cycles of drought and amelioration in agreement with other paleo-climate records of New Mexico. Moreover, the dynamics of salinity and turbidity indicator species, coupled with the emergence of acidophilic species and decline of alkaliophilic species, during drought conditions imply Santa Fe Lake has gone through periods of drought-induced acidification.
An intense century-level drought cycle between 600-200 YBP?

In addition to the evidence of diatom-inferred drought cycles in Santa Fe Lake, there are data suggesting there was an atypically intense dry period in New Mexico between 600-200 YBP. First, the SiZer analysis of the tree ring data of Grissino-Mayer (1995, 1996) indicates an extended drying period between 671-204 YBP, but these decreases in precipitation were no more intense than other periods (Fig. 2). These data are corroborated by speleothem data from southern New Mexico (Rasmussen et al. 2006) that indicate a dry period between 586-393 YBP. However, this drying period between 586-393 YBP was inferred from a hiatus of speleothem growth, suggesting extreme moisture depletion during this period. Furthermore, the solar activity (Reimer et al. 2004) was at its weakest between 665-148 YBP (Fig. 3); reductions in solar activity have been linked to drought (Yu and Ito 1999). This observation suggests there was the possibility for atypically intense periods of sun-modulated drought.

My analyses of Santa Fe Lake suggest that the drying period between 600-200 YBP was unusually intense. Specifically, the diatom PC1 scores became the most positive ( driest) of all the values along the continuum between 600-200 YBP (Fig. 5). Also, the organic matter of Santa Fe Lake was at its lowest (least productive) during the same interval (Fig. 5). It is also possible that more dust was deposited into the lake during this period, reducing the organic content. Moreover, the relative abundance of the drought indicator species *A. distans* var. *alpigena*, *C. meneghiniana*, *N. radiosa* var. *radiosa*, and *S. tenera* were at their highest peaks during ca. 600-200 YBP (Fig. 8). Conversely, the relative abundance of *S. construens* var. *construens* was at its lowest nadir during the same period (Fig. 8), suggesting Santa Fe was the most acidic at this point during the last 2000 years. Collectively, the data from Santa Fe Lake,
coupled with the solar activity record, offer insight about a possible major drought cycle between ca. 600-200 YBP.

Differences in the interpretation of solar-modulated droughts

While the research of solar-modulated drought is a rapidly growing field, patterns of this interaction are largely unresolved. Specifically, it is not understood if patterns of changing solar activity and drought occurrence have global teleconnection or if the phenomena are regionally isolated. For example, Bond et al. (2001) suggested that reductions in solar activity are linked to decreased monsoon activity and decreased precipitation in the Atlantic lower latitudes. Also, decreases in the Asian monsoon have been coupled to decreases in solar activity (Neff et al. 2001, Fleitmann et al. 2003, Wang et al. 2005). Similarly, Yu and Ito (1999) demonstrated that reduced solar activity corresponded with drought periods in the Great Plains of the USA. However, Asmerom et al. (2007) indicated that increased solar activity also induced droughts in southern New Mexico. These discrepancies identify three important points: the linkage of solar activity on drought activity is not thoroughly understood, cycles may not be globally teleconnected, and additional research in the field is needed.

My interpretation of decreasing solar activity and droughts in northern New Mexico is additional information that could be used in further resolving patterns of solar-induced precipitation changes. While I am unsure about the mechanisms of this connection, particularly because it is the opposite conclusion reached in southern New Mexico (Asmerom et al. 2007), I can offer some suggestions for this discrepancy.

First, a possibility to consider is the difference between speleothem, diatom, and tree ring responses to seasonal precipitation. Betancourt et al. (2002) directly tested the tree ring data of
Grissino-Mayer 1995, 1996) against the speleothem data reported in Rasmussen et al. (2006) and found no correspondence. Typically, speleothems in New Mexico are highly sensitive to winter precipitation (Rasmussen et al. 2006). In contrast, diatoms are normally obligate representatives of environmental changes that occur during the summer growing season (Smol 1988, Wetzel 2001). Likewise, tree rings mostly indicate summer growing season precipitation (Grissino-Mayer 1995, 1996). This seasonal discrepancy alone can drastically alter interpretations of precipitation regimes, especially when put into an El Niño-Southern Oscillation (ENSO) context. Specifically, during ENSO events, the southwestern USA has different precipitation regimes for summer and winter. Warm ENSO events cause wet winters and dry summers (Barry and Chorley 1999). Conversely, cold ENSO events cause dry winters, whereas the summers are minimally impacted (Barry and Chorley 1999). Therefore, if solar activity modulates ENSO activity, then there is an intrinsic disconnect between speleothem and diatom-inferred records of precipitation regimes. If this is the case, it is possible that both interpretations about solar-induced droughts (or reverse thereof) are correct when considering the season that each proxy was modulated.

Furthermore, Gutzler (2000) found an inverse relationship between spring snow pack and summer precipitation in New Mexico. Specifically, if mountainous snow packs were thick in the spring from increased winter precipitation, then the immediately following summer had reduced precipitation. The speleothem data from Rasmussen et al. (2006) and Asmerom et al. (2007) represent southern New Mexico winter precipitation, whereas the Santa Fe Lake diatoms and tree rings proxies (Grissino-Mayer 1995, 1996) represent summer precipitation in northern New Mexico. Therefore, it is likely that periods of increased winter precipitation caused increased
speleothem growth in southern New Mexico, but then led to thicker snow packs in the north, which subsequently reduced summer precipitation in the north.

In addition to snow pack data, there are other lines of evidence suggesting a north-south gradient in differential precipitation for New Mexico. The records of Rasmussen et al. (2006) and Asmerom et al. (2007) from southern New Mexico proxies suggested that ENSO is the major modulator of precipitation in southern New Mexico. Molles and Dahm (1990) demonstrated that ENSO more strongly increases precipitation in southern New Mexico than in northern New Mexico. These gradients may explain the variation between speleothem-inferred precipitation in southern New Mexico and diatom- and tree ring-inferred precipitation in northern New Mexico. Additionally, the contribution of summer monsoon precipitation towards the annual total is greater in southern New Mexico than in the northern part of the state (Williams and Ehleringer 1996, Sheppard et al. 2002). Since ENSO intensity has an effect on northern migration of the southwestern monsoon (Sheppard et al. 2002), solar-modulation could potentially cause differentials in north-south precipitation patterns in New Mexico. Specifically, if increased solar intensity increases cold ENSO events, which decreases winter precipitation and monsoon migration as predicted by Asmerom et al. (2007), then southern New Mexico would be more severely drought-impacted than northern New Mexico during solar peaks. Also, Strong et al. (2007) found that humid parcels of air in New Mexico had different sources depending on their altitude. Humid parcels at low altitudes originated from evaporated Gulf of Mexico water, whereas the humid parcels in higher altitudes originated from the Pacific Ocean. This implies that low altitude speleothems from southern New Mexico and high altitude lakes (Santa Fe Lake, 3530 m) and tree rings (El Malpais, 2423 m) in northern New Mexico receive much of their precipitation from different moisture sources. Therefore, it is possible that any change in oceanic
circulation, Walker circulation, or solar intensity (or all three) would have differential effects on precipitation along a north-south gradient.

The explanations I have offered about solar-modulated precipitation differentials are not exhaustive, but they do provide some conceptual reasons for these differences. Further research on the topic is warranted, which will likely resolve these contrasting interpretations. Nonetheless, the sum of these discrepancies highlight drastic differences in regional precipitation regimes that in turn, exemplifies the need for additional climate change studies at the regional scale.

Conclusions

The diatom record in Santa Fe Lake was found to be a reliable surrogate of drought conditions in New Mexico. Climate-driven diatom responses, as interpreted from the literature, followed corroborating evidence of an independently derived tree ring record of drought in New Mexico. Also, data from this study provides additional evidence for the prevalence of drought-induced acidification in lakes, which could become a growing problem in many other regions due to anthropogenic pollution and further climate change (Arnott et al. 2001, Faulkenham et al. 2003). Moreover, I was able to demonstrate a near-zero lag in solar intensity modulation of the diatom community in my study lake. Drought-induced changes in diatoms closely matched solar activity, suggesting decreased solar intensity is a major driver of drought near Santa Fe Lake. Since climate models often disagree over predictions of drought in the middle latitudes, my analyses suggest another path of evidence about a forcing mechanism causing droughts that should be investigated further in the southwestern USA.
Another objective of my study was to generate an alternative interpretation of the nearly modern climate analog in New Mexico, especially since recently derived independent records have some disagreement. My diatom PC1 analyses closely matched, both statistically and visually, records of drought and solar intensity. My interpretation of solar-modulated drought induction in northern New Mexico contradicts data from southern New Mexico, suggesting a north-south differential. Furthermore, the solar intensity has concomitantly increased over the last 200 years, which at least suggests the potential for increased precipitation over this time; diatom PC1 closely matches this trajectory as well. This is not to say that the recent weather has not changed or that future climate will not rapidly become drier, and is certainly not an attempt to disregard the speleothem interpretation of the nearly modern analog. It is certainly possible that long-term patterns in winter precipitation have declined in New Mexico, whereas summer precipitation increased over the last 200 years of my sedimentary record. My objective was to provide a statistically verified interpretation of climate change, which will certainly aid in better resolving climate modeling and drought interpretation in the middle latitudes. Moreover, my statistical methods and analyses presented here provide a suggestive framework for future work in paleo-climate studies.
LITERATURE CITED


D’Antonio, J.R. 2006. The impact of climate change on New Mexico’s water supply and ability to manage water resources. New Mexico Office of the State Engineer/Interstate Stream Commission, available online at www.ose.state.nm.us/more_info_drought_status.html. Last accessed on 8 February 2009.


Holocene climate in the southwestern United States from mites preserved in stalagmites. Geology 29:643-646.


APPENDIX 1. Before preparing the data series for cross-correlation analysis (subsequent deletion of certain data points and interpolation of others), I had to determine that smoothing would not alter the prevailing data trends. Autocorrelation analysis indicated a 24-year lag in the tree ring data of Grissino-Mayer (1995, 1996). Also, autocorrelation analysis indicated a 450-year lag cycle in the solar intensity data of Reimer et al. (2004), which is similar to the 440-year solar cycle widely reported in the literature (e.g. Asmerom et al. 2007). Diatom PC1 was autocorrelated throughout the entire series. These collective results indicated that data smoothing would not alter the prevailing data trends if they were smoothed at 24-year or less intervals. Subsequently, I smoothed the tree ring, solar intensity, and diatom PC2 data series using the SiZer log_{10}(h) = 0.986 bandwidth, which is mathematically similar to a 20-year smooth. The following four pages contain graphs showing these data and manipulations.
Autocorrelation coefficients at corresponding lags for the tree ring data (Grissino-Mayer 1995, 1996), solar intensity data (Reimer et al. 2004), and diatom PC1. The dotted lines are the upper and lower 95% confidence intervals.
Similarities between the 20-year smooth and the SiZer $\log_{10}(h) = 0.986$ bandwidth smooth of the tree ring data from Grissino-Mayer (1995, 1996).
Similarities between the 20-year smooth and the SiZer $\log_{10}(h) = 0.986$ bandwidth of the solar intensity data from Reimer et al. (2004).
Similarities between actual diatom PC1 data and their SiZer $\log_{10}(h) = 0.986$ bandwidth smooth.
APPENDIX 2. List of the 80 diatom species documented in Santa Fe Lake, New Mexico. The relative abundances reported refer to the maximum proportion of each species found in any one of the 75 sediment samples along the entire core. The names listed are the most updated versions. Species names in the text include old and new name synonyms because the old names are commonly recognized as ecological indicator species.

<table>
<thead>
<tr>
<th>Species</th>
<th>Maximum relative abundance in any sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achnanthes plonensis</td>
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<td>Achnanthes saxonica</td>
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<td>Achnanthes sp1</td>
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<td>Species</td>
<td>Percentage</td>
</tr>
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<td>------------</td>
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CHAPTER THREE: A DIATOM AND SEDIMENTARY-INFERRED RECORD OF AN OXBOWh LAKE DEVELOPMENT AND A MID-HOLOCENE HYDROGEOLOGIC MAXIMUM IN THE COASTAL PLAIN, ALABAMA, USA

Abstract. I investigated mid-to-late Holocene (5500 YBP to present day) hydrogeological development of the coastal plain in Alabama, USA, using diatom frustules and sedimentary properties sampled from an oxbow lake sediment core. Sedimentary organic matter and diatoms were analyzed using a new time series statistical approach to identify significant changes along the time continuum. These proxies were used to determine the evolution of an oxbow lake from a predominantly lotic system to a fully lentic system. Before $\approx 5500$ YBP, the system was distinctively lotic. After $\approx 5000$ YBP, the oxbow became increasingly disconnected from the main river channel. Also, water levels appeared to have risen to a peak near $\approx 4000$ YBP and then declined until the modern oxbow was formed between $\approx 1770$-$1235$ YBP. Anthropogenic impacts to the watershed were evident after $\approx 800$ YBP. Furthermore, concomitant changes in sedimentation and diatom assemblages provide additional evidence for a hypothesized mid-Holocene hydrogeologic maximum that began around $\approx 5000$ YBP and ended shortly after $\approx 4000$ YBP. This period of inferred extensive inundation in Alabama is similar to the period of maximum flooding between 4600-3800 YBP reported in the South Carolina coastal plain.
INTRODUCTION

Study background

The southeastern United States (USA) coastal plain possesses a unique combination of ancient, Mesozoic river systems and younger, Holocene oxbow lakes, floodplain marshes, and ponds (Gaiser et al. 2001, Ward et al. 2005). Parts of this region are known for having high species richness as a result of the region’s age and lack of glaciation (Ward et al. 2005). Despite being a hotspot for biodiversity and evolutionary biology research (Lydeard and Mayden 1995), comparatively little is known about the Holocene paleo-climate and paleo-hydrogeology of the southeastern USA coastal plain compared to other regions in North America (Gaiser et al. 2001, 2004). Much of this paucity is due to the lack of glacially formed lakes, which are robust paleo-environmental, sedimentary archives that often encompass most of the Holocene epoch (Cohen 2003). Moreover, frequent cycles of flooding, scouring, and desiccation have severely degraded many coastal plain Holocene paleo-environmental sedimentary archives, making historical interpretations difficult (Gaiser et al. 2001).

Much of the current paleo-climate and paleo-hydrogeology information about the southeastern USA is of wide resolution and has come from geologic, pollen, and archeological records. Geologic formations and bathymetry have indicated that sea levels have fluctuated greatly since at least the Paleozoic era, with repeated cycles of water inundation and recession within the coastal plain; however, sea level changes during the Holocene have been smaller than other epochs (Pashin 1993, Mancini et al. 1993, Ward et al. 2005). Pollen records have shown that coastal plain vegetation communities throughout the Holocene were highly plastic. Specifically, long-standing forests of oak and hickory that emerged during Pleistocene glaciation were replaced by pine stands and swamp vegetation during the mid-Holocene as a result of
increased moisture and warmer temperatures from glacial retreat and climate amelioration (Frey 1953, Whitehead 1953, 1972, 1981, Barron 1992, Gaiser et al. 2001). Brooks et al. (1996) used archeological evidence of human settlements coupled with paleo-bathymetry data to infer historical water levels and pond distribution in the coastal plain of South Carolina. They concluded that the mid-Holocene was wetter than present day with deeper and more permanent water depressions and ponds.

Gaiser et al. (2001, 2004) revisited a pond in the South Carolina coastal plain previously studied by Brooks et al. (1996). Using diatom (Bacillariophyta) assemblages, they were able to construct a high-resolution estimation of historical water level changes in the region and demonstrated a substantive transition in the hydrogeology between 6000-3000 YBP. They concluded that standing waters were at the highest levels between 4600-3800 YBP. These trends were inferred from characteristic changes in diatom taxa indicative of rising and falling water tables. From those data, Gaiser et al. (2001, 2004) hypothesized there was a mid-Holocene hydrological threshold in the coastal plain that was crossed due to the combination of glacial retreat, increased precipitation, rising water tables, and eustatic sea level rise. During this hydrogeologic maximum, the predominantly fluvial coastal plain was inundated with water, subsequently filling in many low-lying depressions with standing water. This ultimately created many of the marshes, ponds, and other lentic environments that are present today. After 3800 YBP, precipitation and water tables decreased, and some ponds desiccated, which marked the end of the hydrogeologic maximum.

Despite the high-resolution work of Gaiser et al. (2001, 2004), paleo-ecological and paleo-hydrogeological records from the coastal plain remain patchy and unresolved.

Specifically, spatial patterns of the hypothesized mid-Holocene hydrogeologic maximum (Gaiser
et al. 2001, 2004) remain unknown. The coastal plain contains a multitude of oxbow lakes (Joo
1990, Joo and Ward 1990, Ward et al. 2005), which could be valuable sedimentary archives to
track paleo-hydrogeological patterns in the region. Oxbow lake sediments have been used
elsewhere to infer flooding regimes from analyzing sedimentation rate (Gasiorowski and
Hercman 2005), isotopic composition of sediments (Lobo et al. 2001, Wolfe et al. 2006), and
changes in diatom assemblages (Wolfe et al. 2005). Sokal et al. (2008) created a high-resolution
meta-analysis of diatom assemblages from 41 shallow lakes, including oxbows, in a river system
in Canada to show net water flow in the floodplain system. Therefore, investigation of oxbow
lake diatom assemblages and sedimentary properties in the USA coastal plain should help
resolve the paleo-hydrogeology of the region.

My study addresses the deficiency in paleo-ecological records of inferred hydrogeology
of the coastal plain by investigating the diatom community and sedimentation in a floodplain,
ombow lake sediment core from Alabama.

Study objectives and hypotheses

The overall emphasis of my study was to use diatoms and sedimentary data from an
Alabama coastal plain oxbow lake to test for the presence of the mid-Holocene hydrogeologic
maximum reported in Gaiser et al. (2001, 2004). I also explored changes in these proxies to
track the transition of the oxbow lake from a predominantly lotic environment to a
predominantly lentic one. The following hypothesis was tested:

H1: Fluctuations in water levels and movement changed diatom community structure and
sedimentation in my study lake. Based on diatom community structure and
sedimentation patterns, it will be possible to determine when the oxbow cutoff was a predominantly lotic environment and when it became the current lentic environment. Also, these proxies can be used to determine the presence or absence of the hydrogeological maximum reported in Gaiser et al. (2001, 2004).

As part of my overall approach to resolve this hypothesis, I applied newly derived statistical methods to the proxies to test for significant transitions within the sediment core through time. The results reported here will advance the paleo-climatology and paleo-hydrogeology records of the southeastern USA, an under-investigated area when compared to other regions in North America.

**Study importance**

This study employs an application of statistical analyses on diatom community dynamics and sedimentation properties over a long-term time series. Commonly, paleo-limnology studies have not used statistical time series analyses to quantitatively determine statistically significant changes through time. I argue that incorporating statistics into paleo-limnological analyses should be paramount in environmental reconstructions. The ability to collect large amounts of data from many variables over long-term time series is one of the most visible strengths of paleo-limnology. However, long-term time series, especially biological sources of climate proxies, often have large amounts of covariance (Woodcock 1992) and noise (von Storch et al. 2004). Covariance and noise can obscure actual trends and/or produce type-1 errors by creating the appearance of changes when none are statistical realities. Therefore, in order to test rigorously the ability of diatoms as indicators of paleo-hydroperiod conditions, it is absolutely necessary to
statistically account for noise in the data and to identify actual data trends. Specifically, because diatoms are often cosmopolitan with rapid dispersal, it is vital to analyze statistically whether a population emergence or decline is a random, noisy phenomenon or if it is conclusively linked to some concomitant environmental process. Diatom paleo-limnology studies have traditionally been highly descriptive and informative, but a need for quantitative null hypothesis testing remains. My approach is the first diatom paleo-limnology analysis to use a newly derived time series analysis (SiZer [Zhang and Marron 2005, Rondonotti et al. 2007]) in order to filter out noise and calculate statistically significant changes in diatom communities and sedimentation over time.

Furthermore, my study provides much needed additional information that is helpful in resolving the Holocene paleo-hydrogeology of the coastal plain. The hypothesized hydrogeological maximum of Gaiser et al. (2001, 2004) suggests that post-glaciation rising sea levels were able to inundate sufficiently the coastal plain and transform a predominantly fluvial ecosystem into an environment with many lakes and ponds. If sea levels were to rise in the future, it would be extremely valuable to have a baseline understanding of the hydrogeological patterns of inundation within the coastal plain.

**METHODS**

*Study site*

Touson Lake (N 33° 00’ 15.7”, W 87° 39’ 51.1”) is an oxbow lake (A₀ = 7.5 ha, Zₘ = 6.3 m, previously estimated as > 500 years old [Joo and Ward 1990]), located in the floodplain of the Black Warrior River ca. 2.5 km west of Moundville, Alabama, and ca. 300 km north of the Gulf of Mexico (Fig. 1). The lake is privately owned and experiences minimal direct anthropogenic
FIG. 1. Location map of the study site, Touson Lake, Alabama.
perturbations (e.g. fishing, water crafts, point-source pollution). However, agriculture is prevalent within the lake basin, which likely contributes some level of nutrient addition. Physiochemical characteristics and patterns of primary production have been previously studied in Touson Lake (Joo 1990, Joo and Ward 1990, Joo and Ward 1991). A series of locks and dams were installed along the Black Warrior River beginning ca. AD 1910. According to Joo (1990) and Joo and Ward (1990), the lake maintains overland, hydrogeologic connectivity during occasional periods of flooding with the Black Warrior River, although the channel has been cut off, and the river is now partially regulated by dams. The current mean annual air temperature of Moundville is 17.1° C, with a mean January temperature of 7.2° C and a mean July temperature of 27.6° C. The mean annual precipitation is 136.9 cm.

**Sediment core**

In November AD 2004 I retrieved a continuous 701 mm sediment core from the deepest portion of the lake by using a 6.5 cm wide core barrel attached to a modified Glew gravity corer (Glew 1989). Upon retrieval, the core was stored at a constant temperature of 4° C until removed for analyses. Within the laboratory, the core was extruded and sectioned into 141 discrete 5 mm sections. Approximately 1 g wet mass was taken from each 5 mm sub-sample for diatom analyses. The remaining portion of each sub-sample was dried at 50° C until a constant mass was obtained. Once a constant mass was obtained, the sub-samples were finely ground with a mortar and pestle. Approximately 1 g dry mass from each 5 mm sub-sample was combusted at 550° C for 24 hours to determine organic content from loss on ignition (LOI). After combustion, samples were weighed, rehydrated with deionized water (18 megohm-cm resistivity), dried, and weighed again to account for any loss of water of hydration.
Additionally, seven uncombusted sub-samples in the sedimentary sequence were sent to the National Ocean Sciences Accelerator Mass Spectrometry Facility, Woods Hole, Massachusetts for reservoir-corrected (present day = AD 1950; calibration data from INTCAL 98 [Stuiver et al. 1998]) $^{14}$C dating of bulk organic matter taken from the depths of 0 mm (top of core), 56 mm, 201 mm, 301 mm, 411 mm, 406 mm, 591 mm, and 701 mm. These depths were chosen because they were either at approximately evenly spaced intervals or they were potential transitional horizons as inferred from color and/or compositional changes. The age-depth profile was fitted with a three parameter sigmoidal regression. Because of the extrapolation of estimated dates between each known $^{14}$C date, all extrapolated dates will be noted with the symbol “$\approx$” throughout the text. The bottom of the core dated 5500 YBP $\pm$ 35 years. Each 5 mm sample averages $\approx$ 39 years of sedimentation with considerable variation along the length of the core.

Diatom enumeration

I digested the ca. 1 g wet mass of lake sediments from each 5 mm sub-sample designated for diatom analyses following the guidelines of Battarbee (1986). Wet samples were first washed with 10% HCl and rinsed with deionized water (18 megohm-cm resistivity) to remove any carbonates. Then, they were digested with 30% H$_2$O$_2$ to remove organic matter and given a final rinse with deionized water. At this point, only silicates remained suspended in deionized water. To avoid damaging any frustules, all suspended samples were allowed to settle via gravity for 24 hours after each washing and rinsing sequence in lieu of centrifuging. No sieving was necessary because the sediments were devoid of coarse-grained (> 0.5 mm) organic and inorganic debris. Also, separation of diatoms via suspension in heavy liquids was not necessary.
Finally, washed samples were allowed to evaporate on glass cover slips before permanently mounted on glass slides with Naphrax (refractive index = 1.65).

Diatom species were identified by use of 1000X phase-contrast microscopy with a Zeiss Axioskop microscope following the taxonomy of Patrick and Reimer (1966, 1975), Williams and Round (1987), and Wehr and Sheath (2003). All species taxonomy and names were updated and verified with the Integrated Taxonomic Information System database (ITIS) and the North American Diatom Ecological database with information current as of December 2008. When possible, at least 300 frustules per 5 mm sample were counted to determine the relative abundance of each species. When it was not possible to enumerate 300 frustules per sample due to diatom paucity, four slide transects encompassing 50 fields of view were counted. Also, broken frustules were ignored unless the broken valves had enough material (usually > 50% of the valve remaining) to allow proper species identification with the dichotomous key. In total, 40,608 frustules from a total of 62 species from 31 genera were identified and enumerated.

**Statistical analyses**

I analyzed the diatom relative abundance data in three steps. Before analyzing, any diatom species that composed < 0.5% of the relative abundance of any depth profile was removed from the database. This reduced the original 62 species to 61 species used for further analyses. For the first step, the relative abundance matrix was normalized using the arcsine-square root transformation (Gotelli and Ellison 2004). Second, to reduce the dimensionality of the diatom community and to identify important individual species, I performed principal components analysis (PCA) on the variance-covariance matrix of the normalized diatom relative abundance data over the 141 sub-samples. PCA is appropriate for the multicollinearity often
found in time series and relative abundance data (Gotelli and Ellison 2004). I used the variance-covariance matrix because it preserves random noise in the variables, it preserves the sums of the variances, and PCA assumes that large variances in the matrix have large dynamics in PCA space. All of these aspects are important when identifying data noise and true trends, especially within newly created multivariate PCA variables (Johnson 1998). Each principal component (PC) point along a PCA axis is a factored representation of the entire diatom community at that specific point. The major species loadings on each PCA axis indicate the ecological characteristics of the community at each step. Third, I analyzed the newly created PCA axes with SiZer (significance of the zero crossings of the derivative). SiZer is a statistical technique that applies a series of smoothing functions based on bandwidths around the data to statistically analyze which data in a matrix or series are true trends and which data are noise or are attributable to sampling variation (Zhang and Marron 2005, Rondonotti et al. 2007). Essentially, SiZer identifies the true modality of the data by applying derivatives; where there is a significant zero crossing of the derivative ($\alpha = 0.05$ around confidence interval 0), there is a significant shift in the composition of the data structure that is independent of noise or sampling variability. SiZer accomplishes this by accounting for both the overall linear trend of the data as well as alternating oscillations along this trend. SiZer is a freeware application that is distributed from www.wagner.com.

I also applied SiZer to other data analyzed in my study, including the percent organic matter in the sediments determined from LOI and the eight species of diatoms with the strongest PCA loadings. Finally, I applied a correlation analysis between diatom PC1 and organic matter (LOI). All analyses were performed at $\alpha = 0.05$. 
RESULTS

Sediment core characteristics

The chronosequence of the Touson Lake core was established from seven $^{14}$C analyses. Each carbon date was the median calibrated age using a 2-sigma calibrated age range (INTCAL 98, Stuvier et al. 1998). The top sample of the core was $^{14}$C dated as post-present day (present day = AD 1950; 0 YBP ± 50 years) and, thus, was considered as AD 1950 (0 YBP) to maintain consistency with the other six $^{14}$C dates. The bottom of the core (sample from 701 mm) dated to 5500 YBP ± 35 years. The sedimentation rate of Touson Lake was highly variable, ranging between 0.21 mm per year (5 mm ≈ 24 years) at the top of the core, 0.10 mm per year (5 mm ≈ 50 years) in the middle, and 0.71 mm per year (5 mm ≈ 7 years) at the bottom. An age-depth profile of sediment, $^{14}$C age, and $^{14}$C errors are presented in Fig. 2. Each age-depth profile point along the continuum was estimated from a three parameter sigmoidal regression.

The Touson Lake core was dominated by a nearly homogenous mixture of clay and gyttja at all depths from the surface to the bottom. The bulk organic content of the core was generally low and highly variable throughout the core (Fig. 3), ranging from a low of 7.6% (LOI) near the bottom of the core to a high of 15.9% (LOI) near the top of the core. SiZer indicated five significant transitions in the organic matter content between the family of bandwidths in the $\log_{10}(h) = 2.01$ to 2.82 spectra (Fig. 3). At ≈ 4880 YBP the organic content transitioned to a significantly higher proportion of organic matter than the previous running trend. Conversely, at ≈ 3460 YBP the sediments changed to a lower organic content for a short period before again changing to a significantly higher organic content at ≈ 2630 YBP. At ≈ 1770 YBP the sediments made another significant switch to lower organic content until finally changing significantly at ≈ 260 YBP to higher organic content.
FIG. 2. Age-depth profile for the Touson Lake sediment core based on $^{14}$C analysis. The points were best-fit with a three parameter sigmoidal regression. Error bars are age errors generated from fraction of modern $^{14}$C errors.
FIG. 3. Organic content-depth profile for the Touson Lake core determined by loss on ignition (LOI). The line with opaque circles is the original % organic matter data. The dashed line is the linear regression of % organic matter, which is an important component in calculating zero crossings of the derivative. The other solid lines are the SiZer family of bandwidths in the $\log_{10}(h) = 2.01$ to $2.82$ spectra. The open circles indicate points of significant change based on zero crossings of the derivative.
**Diatom community shifts**

The diatom community contained 62 species from 31 genera (Appendix 1) and was highly plastic throughout the depths of the Touson Lake core. PCA extracted one useful axis for further analyses, which accounted for ca. 31% of the total community variance (Fig. 4). PC2 and PC3 accounted for ca. 9% and ca. 6% of the variance, respectively, and were omitted from further analyses.

Eight diatom species were strongly associated with PC1 (communalities > 0.50; Table 1, Fig. 5). Species with the most positive loadings along PC1 included *Aulacoseira distans, A. granulata, Gomphonema gracile,* and *Pinnularia acuminata.* Ecologically, these species are planktonic or have a preference for lentic habitats (Patrick and Reimer 1966, 1975, Wehr and Sheath 2003). Additionally, *Aulacoseira* is a common indicator of turbid water columns or standing, stagnant water (Patrick and Reimer 1966, 1975, Sherman et al. 1998, Licursi et al. 2006). Conversely, PC1 was negatively loaded by *Epithemia argus, G. dichotomum, Hantzschia amphioxys* and *P. abaujensis.* *E. argus* is a benthic species that commonly has endosymbiotic associations with cyanobacteria (Wehr and Sheath 2003). *G. dichotomum* is commonly found in lotic habitats (Patrick and Reimer 1966, 1975, Wehr and Sheath 2003). *H. amphioxys* is an aerophilic species that often indicates mesic conditions or low water levels (Patrick and Reimer 1966, 1975, Gaiser et al. 2000, Wehr and Sheath 2003). *P. abaujensis* has a wide habitat tolerance and can be found in both lentic and lotic habitats (Patrick and Reimer 1966, 1975). Therefore, as PC1 scores became more positive, the relative abundances of *A. distans, A. granulata, G. gracile,* and *P. acuminata* increased, which suggest the local environment had lentic characteristics or areas of standing water; likewise, their decline is indicative of waters becoming less lentic and more transient in nature (PC1 scores become more negative). As the
FIG. 4. Diatom PC1-depth profile for the Touson Lake core. The line with opaque circles is the original diatom PC1 data. The dashed line is the linear regression of the diatom PC1 data, which is an important component in calculating zero crossings of the derivative. The other solid lines are the SiZer family of bandwidths in the $\log_{10}(h) = 2.14$ to 2.95 spectra. The open circles indicate points of significant change based on zero crossings of the derivative.
TABLE 1. The eight diatom species with the greatest individual loadings (cutoff was $> \pm 0.043$ because these species loadings had communalities $> 0.50$) on the first principal component analysis axis.

<table>
<thead>
<tr>
<th>Taxon</th>
<th>PC1 loadings</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Aulacoseira distans</em></td>
<td>0.181</td>
</tr>
<tr>
<td><em>Aulacoseira granulata</em></td>
<td>0.049</td>
</tr>
<tr>
<td><em>Gomphonema gracile</em></td>
<td>0.049</td>
</tr>
<tr>
<td><em>Pinnularia acuminata</em></td>
<td>0.062</td>
</tr>
<tr>
<td><em>Pinnularia abaujensis</em></td>
<td>-0.087</td>
</tr>
<tr>
<td><em>Epithemia argus</em></td>
<td>-0.043</td>
</tr>
<tr>
<td><em>Gomphonema dichotomum</em></td>
<td>-0.161</td>
</tr>
<tr>
<td><em>Hantzschia amphioxys</em></td>
<td>-0.065</td>
</tr>
</tbody>
</table>

Notes: 1Lentic species; 2turbidity-tolerant species; 3wide habitat range species; 4species has endosymbiotic cyanobacteria; 5lotic species; 6aerophilic species (see text for more details)
FIG. 5. Relative abundance-depth profiles for the eight species of diatoms with the most predominant loadings from PCA within the Touson Lake core. The dashed lines are the linear regressions of the diatom relative abundance data, which are important components in calculating zero crossings of the derivative. The other solid lines are the SiZer bandwidths (see text for spectra). The open circles indicate points of significant change based on zero crossings of the derivative.
PC1 scores became more negative, the relative abundances of *E. argus, G. dichotomum, H. amphioxys* and *P. abaujensis* increased, which suggest the local environment became more lotic and/or mesic; likewise their decline is indicative of increased moisture and/or lentic habitats (as PC1 scores become more positive). Ultimately, it appears that PC1, as a whole, is capturing diatom community variance associated with changes in water levels and whether the water is predominantly transient or standing. Furthermore, diatom PC1 was significantly correlated (r = 0.78, p < 0.001) with sedimentary organic matter (LOI).

SiZer indicated that there were two significant changes in the diatom community along the continuum between the family of bandwidths in the log\(_10(h) = 2.14\) to 2.95 spectra (Fig. 4). At \(\approx 5020\) YBP, diatoms significantly changed to more positive PCA scores (from ca. -1.7 to ca. +2.0). After this, at \(\approx 1235\) YBP, the diatoms significantly changed to less positive PCA scores (ca. +2.0 to ca. -0.05).

The eight diatom species with the highest PCA loadings and communalities along PC1 were highly plastic in their relative abundances through time (Fig. 5). Seven of these eight species demonstrated significant (via SiZer) changes in relative abundances throughout the time series. *A. distans* consistently had the highest relative abundances (up to ca. 31%) of the community. *E. argus* and *P. abaujensis* were also prevalent along the length of the core, with relative abundances up to ca. 23% and ca. 17%, respectively. The remaining five species were more ephemeral.

The relative abundance of *A. distans* had three significant changes along the long-term time series. SiZer (bandwidths in the log\(_{10}[h] = 2.36\) to 3.17 spectra) indicated that the relative abundance significantly increased between \(\approx 5075\text{-}2340\) YBP and from \(\approx 470\) YBP to present. Conversely, between these increasing intervals, the relative abundances significantly decreased
from \( \approx 2340-470 \) YBP. *A. granulata* had lower relative abundances than *A. distans* and was more ephemeral. SiZer (bandwidths in the \( \log_{10}[h] = 2.36 \) to 3.17 spectra) indicated that the relative abundance significantly decreased between \( \approx 4000-270 \). Conversely, after this interval, the relative abundance significantly increased from \( \approx 270 \) YBP to present.

*G. gracile* had one significant transition (SiZer bandwidths in the \( \log_{10}[h] = 1.90 \) to 2.59 spectra) between \( \approx 5010-4400 \) YBP when it had higher abundance than any other portion in the core. *G. dichotomum* had its highest relative abundance around \( \approx 5500 \) YBP and then decreased about \( \approx 5000 \) YBP. It became locally extirpated at \( \approx 3875 \) YBP. However, SiZer deemed none of these changes as statistically significant transitions.

*P. acuminata* had one significant change in its relative abundance over time. This significant change (SiZer bandwidths in the \( \log_{10}[h] = 1.90 \) to 3.05 spectra) was between \( \approx 1390-490 \) YBP when the relative abundances were significantly greater than the remainder of the time series. *P. abaujensis* was more prevalent throughout the core than *P. acuminata*, and had two significant transitions in abundance (SiZer bandwidths in the \( \log_{10}[h] = 1.90 \) to 2.94 spectra). Between \( \approx 3100-840 \) YBP, the relative abundances were significantly greater than the remainder of the time series.

The relative abundance of *E. argus* had four significant changes in relative abundance over time. SiZer (bandwidths in the \( \log_{10}[h] = 1.90 \) to 3.05 spectra) indicated that the relative abundance significantly increased between \( \approx 5315-4600 \) YBP and from \( \approx 2490-510 \) YBP. Conversely, between these increasing intervals, the relative abundances significantly decreased from \( \approx 4600-2490 \) YBP and \( \approx 510 \) YBP to present.

*H. amphioxys* was relatively rare throughout the core, with its greatest abundance occurring before \( \approx 4990 \) YBP. After this point, the abundances became permanently and
DISCUSSION

The main objectives of this study were to reconstruct the paleo-hydrogeology of Touson Lake and test for the presence of a coastal plain, mid-Holocene hydrogeologic maximum in Alabama. This maximum was previously reported to have occurred in South Carolina by Gaiser et al. (2001, 2004), but corroborating evidence from other regions in the southeastern USA is sparse. There is, however, some evidence of large-scale expansion of wetlands after 6500 YBP. Specifically, extensive flooding caused the formation of the Okefenokee Swamp in Georgia (Cohen 1973). Also, the Florida Everglades were formed during the same period by similar flooding and precipitation patterns (Dovell 1947, Gleason and Stone 1994). Nevertheless, these landscape formations were traditionally thought to be isolated events that were unique combinations of flooding, plant decay, anaerobic metabolism, and peat formation (Cohen 1973). My study provides evidence of a broader pattern, both in space and time, of coastal plain inundation.

Touson Lake is currently an oxbow lake that was formerly part of the main channel of the Black Warrior River. As a result, it had declining connectivity with the main channel through time as the meandering neck was eroded. Oxbow lake ontogeny is often estimated from changes in basin morphometry and vegetational succession, especially water tupelo (Nyssa aquatica) and bald cypress (Taxodium distichum) (Harper 1912, Melack 1984, Joo 1990, Joo and Ward 1990). However, changes in sedimentation rate and primary productivity can often be used to determine the chronology of oxbow lake formation (Joo and Ward 1991, Lobo et al. 2001, Gasiorowski and
Specifically, on a per area unit basis, unconfined floodplains have higher productivity than confined river channels and standing lakes (Woodwell et al. 1978, Lobo et al. 2001, Wetzel 2001). Furthermore, older oxbow lakes (> 500 years old) can be more productive than younger oxbows (< 100 years old) (Joo and Ward 1991).

Therefore, it was possible to infer the paleo-hydrogeology of the Touson Lake basin using a combination of sediment and diatom proxies. Decreases in organic matter and/or sedimentation rate often signify reductions in production over time, and vice versa. Likewise, diatom species are often obligate lentic or lotic species; assessing changes in community characteristics can infer changes in the aquatic environment. The sediment and diatom profiles of Touson Lake showed significant changes through time, and these shifts were likely caused by changes in aquatic habitat type and availability. As diatom PC1 scores became more positive, the species composition was characteristic of a productive lentic environment. As the PC1 scores became more negative, the species composition was characteristic of a less productive lotic environment. Ultimately, it appeared that changes in the water table and floodplain, from both the mid-Holocene hydrogeologic maximum and oxbow isolation, changed the availability of lotic and lentic habitats in the Touson Lake basin.

The insights gained from applying SiZer analyses to the diatom community and sedimentary data permitted statistical identification of specific points in time when the proxies significantly changed from one dominant profile to another. Specifically, the use of SiZer elucidated when sedimentary facies transitioned from lotic to lentic. Also, it indicated when the major indicator diatoms of Touson Lake statistically shifted from lotic indicator species to lentic indicator species. Then, these shift points were compared to other records in the coastal plain. If mid-Holocene inundation was present in Alabama, it should approximate the record of
inundation in South Carolina (Gaiser et al. 2001, 2004). The results from my study suggest that
the southeastern USA coastal plain was more inundated than previously thought.

My overall interpretation of the hydrogeology of Touson Lake based on sedimentation and diatom
assemblages is that the water body went through four major transitions during the last ca. 5500 years. Between \( \approx 5500-5000 \) YBP, the system was predominantly lotic. After \( \approx 5000 \) YBP, the system became distinctively lentic. Specifically, water tables appeared to have risen around \( \approx 5000 \) YBP and reached a maximum level near \( \approx 4000 \) YBP. Then, after \( \approx 4000 \) YBP, water levels declined until \( \approx 1770-1235 \) YBP when the modern oxbow likely emerged. This pattern of a rising and falling water table is consistent with the paleo-hydrogeology found in the coastal plain of South Carolina reported in Gaiser et al. (2001, 2004). Most recently, anthropogenic effects likely began to impact the basin around \( \approx 800 \) YBP.

First period, \( \approx 5500-5000 \) YBP

Between \( \approx 5500-4880 \) YBP, sedimentation rates were the highest of all samples throughout the entire core series, but organic matter content was among the lowest. This suggests the Touson Lake channel may have been a newly forming oxbow that received sediment infill from the main Black Warrior River channel. During early oxbow formation, sedimentation rates are often the highest during its entire ontogeny because planktonic autochthonous production from within the newly forming lake is combined with an abundance of allochthonous deposition from the main channel (Gasiorowski and Hercman 2005). Furthermore, vertical sediment accretion is often the greatest of all depositional environments in areas adjacent to the main river channel (Hupp 2000). Flowing waters have higher energy to transport sediment loads than lentic waters; when the main channel is above bank full stage,
water enters the floodplain or an oxbow, flow velocity and energy are greatly reduced, and sediments are rapidly deposited (Hupp 2000, Lobo et al. 2001). Also, fluvial sediments typically have lower organic content than lentic sediments (Lobo et al. 2001, Wetzel 2001).

Corresponding with this sedimentation, diatom PC1 was dominated by lotic species between \(\approx 5500-5020\) YBP. This further suggests the presence of a river channel before \(\approx 5020\) YBP. Two of the eight diatom species with the strongest PC loadings, *G. dichotomum* and *H. amphioxys*, had their greatest relative abundances before \(\approx 5020\) YBP. *G. dichotomum* is a species commonly found in lotic environments (Patrick and Reimer 1966, 1975, Wehr and Sheath 2003). *H. amphioxys* is an aerophilic species that often indicates mesic conditions and/or low water levels because it lives in soils and on plants adjacent to river channels (Patrick and Reimer 1966, 1975, Wehr and Sheath 2003). Gaiser et al. (2001) used *H. amphioxys* emergence as an indicator of dry hydroperiods and low water tables in the coastal plain of South Carolina. Likewise, its decline was used to infer rising, lentic water tables.

*Second period, \(\approx 5000-1770\) YBP*

SiZer indicated significant transitions in both organic matter and diatoms around \(\approx 5000\) YBP. This likely marked an increase in the water table and a transition from a lotic environment to an increasingly lentic one. Abrupt changes in organic content facies are strong indicators of lotic to lentic transitions (Lobo et al. 2001). In Touson Lake, after \(\approx 4880\) YBP, sedimentation rates decreased, but organic content significantly increased. This suggests the basin transitioned for two main reasons. First, because the sedimentation rate decreased, it was likely that the oxbow channel received less allochthonous deposition from an actively connected river channel. As oxbows develop, cutting and concomitant depositional forces through the meandering neck
by the active channel form earthen dams that reduce connectivity with the main channel, which lowers allochthonous deposition (Hupp 2000, Wetzel 2001, Gasiorowski and Hercman 2005). Furthermore, vegetation rapidly colonizes these earthen dams, which further curtails sediment infill (Melack 1984, Joo 1990, Joo and Ward 1990, Hupp and Osterkamp 1996). Second, because organic content of the sediments increased, it was likely that the aquatic environment became a predominantly unconfined lentic environment after \( \approx 4880 \) YBP because of the differential productivity between confined and unconfined water channels (Woodwell et al. 1978).

Concomitantly, after \( \approx 5020 \) YBP, the diatom community significantly transitioned to more positive PC1 scores, and became more characteristic of a lentic environment. The most abundant species after \( \approx 5020 \) YBP was \( A. \) distans. \textit{Aulacoseira} is a centric, planktonic genus commonly used as an indicator of standing and turbid water (Sherman et al. 1998, Licursi et al. 2006). Furthermore, Gaiser et al. (2001) used \textit{Aulacoseira} as an indicator of rising water levels, the onset of the mid-Holocene hydrogeological maximum, and an abundance of standing water in the coastal plain. In Touson Lake, lentic \( A. \) distans rapidly increased in abundance between \( \approx 5075-4000 \) YBP, suggesting an increase in water levels. Additionally, the abundance of \( A. \) distans suggests that the standing water was also turbid, which would be expected in expansive, organic-rich floodplain marshes (Hupp 2000, Wetzel 2001). This rise in water table is further corroborated by the significant emergence of \( G. \) gracile at \( \approx 5010 \) YBP, which is also a lentic indicator species (Patrick and Reimer 1966, 1975, Wehr and Sheath 2003).

The decline of the lotic species, \( G. \) dichotomum, after \( \approx 5000 \) YBP and its final extirpation after \( \approx 4000 \) YBP provide additional evidence that the Touson Lake channel became separated from the Black Warrior River and/or water levels rose above the river banks for
extended periods of time. This is concordant with the significant decline of the aerophilic species *H. amphioxys* after \( \approx 4990 \) YBP. Its decline indicates the channel banks were exceeded with long-standing pools of water within the floodplain.

However, it appears that the lentic environment was caused by large-scale, lateral floodplain inundation rather than just the formation of a cutoff oxbow. The oxbow may have been fully cut off from the main channel as early as \( \approx 4880 \) YBP, but this process would have been in addition to large-scale lateral flooding throughout the watershed. This is evident because organic matter rapidly increased between \( \approx 4880-4000 \) YBP, and then rapidly declined thereafter. There was some oscillation, but the general trend showed a significant reduction at \( \approx 3460 \) YBP followed by another significant reduction at \( \approx 1770 \) YBP. The basin was the most productive throughout its history near \( \approx 4000 \) YBP, which suggests that waters rose to the highest level between \( \approx 4880-4000 \) YBP, and have continued to decline ever since. Oxbow lakes often fill in with sediments on the scale of hundreds of years, rather than thousands of years (Weihaupt 1977, Joo 1990, Joo and Ward 1990). Therefore, it was likely that the Touson basin became a fully cutoff oxbow more recently than \( \approx 4880 \) years ago. The lentic conditions in the Touson Lake area between \( \approx 4880-4000 \) were likely caused by another hydrogeologic process, which may have been the mid-Holocene hydrogeologic maximum reported in South Carolina between 4600-3800 YBP by Gaiser et al. (2001, 2004).

Diatoms corroborate the interpretation of decreasing water levels after \( \approx 4000 \) YBP. After its peak abundance at \( \approx 4000 \) YBP, lentic *A. distans* began to decline in numbers and significantly transitioned to lower relative abundances at \( \approx 2340 \) YBP. Also, lentic *G. gracile* significantly declined after \( \approx 4400 \) YBP. These declines imply that water levels began to decrease, which reduced the availability of lentic habitat throughout the floodplain. However,
because lotic *G. dichotomum* and aerophilic *H. amphioxys* numbers were still low, this suggests that while the water levels declined, the Touson channel did not resume lotic characteristics; likely, the Touson basin became an increasingly isolated oxbow from near this point forward.

*Third period, ≈ 1770-800 YBP*

The significant transition to lower organic matter at ≈ 1770 YBP may have signaled the transition of the Touson Lake channel into its current oxbow lake bathymetry. Confined lakes are typically less productive on a per area unit basis than expansive floodplains (Woodwell et al. 1978, Wetzel 2001); therefore this evidence suggests the area transitioned from an expansive wetland into an isolated oxbow during this period. Furthermore, sedimentation rates did not change during this period. This implies the main river channel was not reconnected with the Touson oxbow, and it did not introduce allochthonous sediment. Furthermore, Joo and Ward (1990) previously estimated the age of Touson Lake to be > 500 years from basin bathymetry and bald cypress and water tupelo stand composition, which is consistent with the range of my sedimentation-inferred age estimation.

Similarly, SiZer indicated a significant change in diatom PC1 scores after ≈ 1235 YBP. Specifically, *P. acuminata*, which is a lentic species (Patrick and Reimer 1966, 1975), had a statistically significant emergence at ≈ 1390 YBP. However, during this period, *A. distans* (lentic, turbidity indicator) had very low abundances. This combination suggests the water was still lentic, but of lower turbidity than previous years, indicating the Touson oxbow was more isolated from hydrogeologic influences from an expansive floodplain. Additionally, *P. abaujensis* peaked in abundance between ≈ 3100-840 YBP. This species is also a lentic indicator, but has a preference for water with low mineral content (Patrick and Reimer 1966,
1975). Its emergence suggests the Touson Lake basin received less water containing weathered minerals from an expansive river network. The combination of significant changes in organic matter after $\approx 1770$ YBP and in diatom PC1 scores after $\approx 1235$ YBP provide corroborating evidence that the Touson Lake basin began to resemble its modern bathymetry sometime within this period.

*Fourth period, $\approx 800$ YBP to present*

Marked changes in organic matter and diatom composition provided evidence that anthropogenic impacts may have begun to affect the Touson Lake basin as early as $\approx 800$ YBP. Touson Lake is located adjacent to one of the major political/religious centers of the Native American Mississippian culture (Moundville, Alabama) that was occupied from $\approx 1100-500$ YBP and reached its peak between $\approx 800-600$ YBP (Jenkins and Krause 1986, Knight 2004, Ward et al. 2005). A signature characteristic of this society was its cultivation of corn and other crops in the nutrient-rich soils of the Black Warrior River floodplain. Even without the use of modern synthetic fertilizers and other farming aids, such agrarian practices may have had long-term impacts on nutrient and sedimentation regimes in Touson Lake. For example, continuing high total adsorbed phosphorus concentrations in soils in an area in France were attributed to a 200-year period of Roman agriculture that occurred 2000 YBP (Dupouey et al. 2002). Therefore, it is likely that Mississippian culture farming practices may have begun a period of increased productivity in Touson Lake that continued into the AD 21st century. SiZer bandwidth analysis is consistent with this interpretation because it showed an upward trend in organic matter starting $\approx 800$ YBP and continuing to the present.
The most recent increase in organic matter in Touson Lake sediments, as indicated from samples in the time period from \( \approx 260 \) YBP to the present, may have been enhanced by new settlers in the area beginning \( \approx 300 \) YBP. After collapse of the Mississippian culture during the AD 16th century, European immigrants from the eastern USA brought additional row crops, livestock, and deforestation to the coastal plain region (Ward et al. 2005). Also, extensive channelization and construction of locks and dams throughout the Black Warrior River that occurred between AD 1900-1961 likely influenced overall productivity, turbidity, and sedimentation in floodplain habitats, including oxbow lakes (Mettee et al. 1987, Joo and Ward 1990, Ward et al. 1992).

Changes in diatom composition also supported a scenario of significant increase in Touson Lake nutrient enrichment and productivity beginning at the same time as organic matter increases. Six of the eight most important diatoms in the Touson Lake phytoplankton community appeared to have responded to anthropogenic impacts over the last 800+ years, a timeframe associated with the Mississippian culture and European settlement. For example, \( A.\) \textit{granulata} and \( A.\) \textit{distans}, both planktonic species indicative of turbid water (Sherman et al. 1998, Licursi et al. 2006), significantly emerged after \( \approx 270 \) and \( \approx 470 \) YBP, respectively. \textit{Epithemia} is a diatom genus that often harbors endosymbiotic, nitrogen-fixing cyanobacteria (Wehr and Sheath 2003). \( E.\) \textit{argus} abundances were variable throughout the Touson Lake core, but it had a statistically significant decline after \( \approx 510 \) YBP perhaps caused by increases in lake nitrogen resulting from farming practices and/or deforestation that relieved nitrogen limitation and made the introduction of new nitrogen by nitrogen fixation less advantageous. Also, the declines of \( P.\) \textit{acuminata} and \( P.\) \textit{abaujensis}, which both prefer low mineral content, after \( \approx 490 \) YBP and \( \approx 840 \) YBP, respectively, suggest an influx of nutrient and minerals into Touson Lake.
Conclusions

Multiple lines of evidence, from sedimentation rate, sedimentary organic content, and diatom community changes, support my hypothesis and indicate that the Touson Lake basin has undergone several changes in hydrogeology over the last $\approx 5500$ years. The strong correlation between sedimentary organic matter (LOI) and diatom PC1 indicates that both proxies were capturing similar environmental processes. The aquatic environment of the Black Warrior watershed was distinctively lotic before $\approx 5000$ YBP. After this time, evidence suggests that the oxbow became increasingly disconnected from the main river channel. Also, water tables appeared to have risen, creating expansive floodplains. Some time after $\approx 4000$ YBP, water tables declined, but the Touson oxbow remained disconnected from the main channel. Between $\approx 1770$-$1235$ YBP, the Touson basin resembled the modern oxbow lake, which is consistent with a previous study dating the lake to $> 500$ years old (Joo 1990). Recent changes in sediment characteristics and diatom assemblages indicate the lake has been affected by anthropogenic disturbances within the region.

Most importantly, these conclusions are consistent with the hypothesis of a mid-Holocene hydrogeologic maximum in the South Carolina coastal plain between 4600-3800 YBP reported in Gaiser et al. (2001, 2004). I found evidence that water levels in the Alabama coastal plain may have increased around $\approx 5000$ YBP and subsequently declined after $\approx 4000$ YBP. Paleo-hydrogeological records are scarce from the coastal plain, but the combination of my study and previous results collectively show that the coastal plain has been a very dynamic aquatic ecosystem. Furthermore, the increase of water levels in the northern part of the Alabama coastal plain documented in this study is concomitant with the formation of the Okefenokee Swamp and the Florida Everglades, which then demonstrates that the overall southeastern coastal plain had
expansive floodplains and lentic environments during the mid-Holocene. Large-scaled climate changes following the last glaciation shaped the region through a series of hydrogeological processes. Understanding patterns of historical coastal inundation are of value should sea levels rise again.


Cohen, A.D.  Possible influences of subpeat topography and sediment type upon the development of the Okefenokee Swamp-marsh complex of Georgia.  Southeastern Geology 15:141-151.


APPENDIX 1. List of the 62 diatom species documented in Touson Lake, Alabama. The relative abundances reported refer to the maximum proportion of each species found in any one of the 141 sediment samples along the entire core. The names listed are the most updated versions.

<table>
<thead>
<tr>
<th>Species</th>
<th>Maximum relative abundance in any sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amphora ovalis</td>
<td>0.077</td>
</tr>
<tr>
<td>Asterionella formosa</td>
<td>0.066</td>
</tr>
<tr>
<td>Aulacoseira distans</td>
<td>0.308</td>
</tr>
<tr>
<td>Aulacoseira granulata</td>
<td>0.180</td>
</tr>
<tr>
<td>Calanois sp1</td>
<td>0.025</td>
</tr>
<tr>
<td>Cocconeis minutum</td>
<td>0.071</td>
</tr>
<tr>
<td>Cyclotella meneghiniana</td>
<td>0.217</td>
</tr>
<tr>
<td>Cymbella cuspidata</td>
<td>0.027</td>
</tr>
<tr>
<td>Cymbella lanceolata</td>
<td>0.027</td>
</tr>
<tr>
<td>Diatomata vulgar</td>
<td>0.009</td>
</tr>
<tr>
<td>Diploneis sp1</td>
<td>0.031</td>
</tr>
<tr>
<td>Encyonema müelleri</td>
<td>0.037</td>
</tr>
<tr>
<td>Encyonema silešiácum</td>
<td>0.143</td>
</tr>
<tr>
<td>Epithemia argus</td>
<td>0.229</td>
</tr>
<tr>
<td>Eunotia curvata</td>
<td>0.156</td>
</tr>
<tr>
<td>Eunotia maior</td>
<td>0.228</td>
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<tr>
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<tr>
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<tr>
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<tr>
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<tr>
<td>Hantzschia amphioxys</td>
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<tr>
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</tr>
<tr>
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<tr>
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<tr>
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<tr>
<td>Neidium sp1</td>
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<tr>
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<tr>
<td>Species</td>
<td>Percentage</td>
</tr>
<tr>
<td>---------------------------</td>
<td>------------</td>
</tr>
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<td><em>Stauroneis anceps</em></td>
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<td><em>Stauroneis phoenicenteron</em></td>
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<tr>
<td><em>Stauroneis schinzii</em></td>
<td>1 valve was counted in core</td>
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<td><em>Tetracyclus sp1</em></td>
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OVERALL CONCLUSION

The lack of an adequate ancient analogue for future climates means that we ultimately must use and trust climate models, evaluated against modern observation and our best geologic records of warm and cold climates of the past. Armed with an elevated confidence in the models, we will then be able to make reliable predictions of the Earth’s response to our risky experiment with the climate system.


My overall objective of the research presented here was to assess the range of possible historical climate changes in three regions with distinctively different climates: sub-arctic Alaska, semi-arid New Mexico, and sub-tropical Alabama. The foremost conclusion from my intersite research was that the uniform suite of climate proxies responded differently in each of these three regions. Specifically, oscillations in the most dominant indicator diatom taxa were asynchronous between all lakes. This suggested that each region was influenced by unique regional-level climate forcing mechanisms rather than a single, invariable global pressure. Diatoms in the Alaska lake changed concordantly with temperature oscillations. In the New Mexico lake, diatom communities responded to long-term cycles of drought. Diatoms and sedimentation data from the Alabama lake demonstrated landscape evolution and changes in post-glaciation precipitation and sea levels. These were important findings because they provided further evidence that global climate change is the sum of concomitant regional alterations that are often more complex than temperature increases alone.

My approach to this research followed two criteria: design an \textit{a priori} cross-regional comparison and analyze the data within each region with new statistical applications. The new
A statistical technique was able to reduce levels of noise in the data and identify true data trends. This was paramount to my study goals because diatoms are often cosmopolitan with rapid dispersal. In order to distinguish differences among ecosystems, I had to identify the statistically most important diatom species, as well as their true data trends, from each sediment core. To do so, I had to determine whether a population increase or decline was a random, noisy event, or if it was a statistically significant phenomenon. Then, if it was a significant event, I could investigate potential environmental causes for these population dynamics. Ultimately, my research approach advanced paleo-limnology through the demonstration of calculating what diatom species were the statistically most important in each lake, determining if and when a significant change in species abundance occurred, and validating why these changes happened against independently derived paleo-climate data.

Paleo-limnology has been a rather subjective field heavily dependent on graphically driven analyses. Usually, a series of depth-species plots (upwards of 80-100 species plots in a single manuscript) are used to identify approximate periods when particular species increased or declined in abundance. Additionally, patterns in diatom taxa increases and declines are typically determined from an arbitrary relative abundance percentage. For instance, a subjective minimum range encompassing 2-9% of relative abundance of any one species in any one sediment sub-sample is often used to determine if a taxon was a major indicator species or not at that specific time interval (cf. Battarbee 1986 and references ibid). Then, these small peaks are used to decipher some climatic event. However, many long-term data series have significant amounts of noise (Woodcock 1992, von Storch et al. 2004). Data falling within the 2-9% range could be erroneously interpreted as a major increase when it is statistically not a real trend. According to statistical theory, most time series population size data exhibit a low frequency noise spectrum.
(red noise) that increases the overall population variance with length of time (Gotelli and Ellison 2004). In other words, type-1 error “false positives,” which suggest a trend is present when the trend in fact does not exist, increase proportionally with the length of the population time series.

As an example of this systematic error, “false positive” diatom-inferred temperature changes were present in my data when using the arbitrary 2-9% relative abundance cutoff. Because the thermometer records from the three study regions showed historic temperature variations over the last century (cf. Chapman and Walsh 1993, EPA 1998a, 1998b Rawlins and Willmott 2003), I expected that diatom assemblages would show long-term temperature changes in each lake. To analyze my diatom data, I used the widely accepted enumeration method of 600 frustules per 1 cm of sediment (cf. Smol et al. 2005). If I adhered to the 2-9% relative abundance cutoff, a minimum range of only 12-54 frustules in any one 1-cm sample constituted a major population increase. To put this into perspective, I enumerated 55,872 diatom frustules in the Alaska core, which was the longest and had the most frustules of all three cores. Therefore, using the 2-9% per sample method, it would hypothetically be possible that a single diatom species contributing 0.02% of the entire core could be interpreted as a climate indicator. While preliminarily using this 12-54 frustule per sample range, I noted that fluctuations in many temperature indicator taxa in the 2-9% range were sporadically spaced throughout all three of my cores, creating the appearance of temperature changes. However these subjectively inferred temperature changes did not match regional or global paleo-climate records reported in the literature.

When statistically analyzing the diatom communities with my chosen objective method, many of these initial temperature change inferences based on 2-9% relative abundance were considered random noise and not true data transitions. The technique I used placed emphasis on
when diatoms changed but also factored in sustained trajectories of increases or declines, rather than patchy data peaks, to determine what diatoms were the most important. More importantly, these insights indicated that the diatoms did not respond to temperature changes in all three of my study sites as initially predicted.

The cross-regional comparison demonstrated why each of my study ecosystems was different. From the determination of when the dominant indicator species significantly changed, it was possible to validate these patterns with regional environmental correlates. The true data structure from each region did not have concordant diatom increases or declines; rather, the patterns observed were unique to each individual lake. Differences in diatom assemblages from one lake to the next are expected; every lake will have varying paleo-limnological trajectories controlled by the prevailing environmental pressures that alter the receiving proxies (Smol and Douglas 2007). Therefore, the central task is to identify these prevailing environmental pressures. Temperature changes undoubtedly affect most diatom communities, but other forcing mechanisms, such as precipitation and landscape evolution, may be more influential on ecosystem production and function in certain regions, overriding any effects temperature changes may cause (Smol 1988, Fritz 1996, Cohen 2003, Smol et al. 2005). My statistical analyses objectively elucidated the most coincidental, dominant forcing mechanisms in each region regardless if the cause was temperature or not. Specifically, the major Alaska diatom profile correlated with paleo-temperatures determined from stable isotopes (data from Hu et al. 2001), the diatom trend from New Mexico correlated with paleo-precipitation inferred from tree rings (data from Grissino-Mayer 1995, 1996), and the dominant Alabama diatom pattern corresponded with other diatom literature from the southeastern coastal plain (data from Gaiser et al. 2001, 2004).
The statistical validation of diatom inferences from independently derived paleo-climate records is a step forward that demonstrates the strong utility of diatoms as *a priori*, cross-regional paleo-climate proxies across diverse environments. There is a strong need for additional, replicated paleo-climate research from regional scales that will improve forecasting model grid resolution (Kump 2002, Brumfiel 2006). Currently, the best forecasting models are in disagreement over possible scenarios caused by anthropogenic perturbations (Kump 2002). Specifically, it has been hypothesized, due to coupled ocean-atmosphere interactions, that an increase in the global average temperature would have varying responses in regional-dependent changes in temperature and precipitation (Crowley and North 1991, Barry and Chorley 1999, Jones et al. 2001). Models currently lack agreement on, and often underestimate, these regional climate variations (Kump 2002). Resolving these regional differences has been an active area of paleo-climatology and climate modeling research (Crowley 2000, Kump 2002, von Storch et al. 2004). The diatom approach is a valuable method capable of discerning climate change responses among different regions that could, subsequently, be applied more broadly across other regions and lead to improved climate change forecasts.
LITERATURE CITED


