

Article

An independently corroborated, diatom-inferred record of long-term drought cycles occurring over the last two millennia in New Mexico, USA

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Abstract

We investigated late Holocene (2000 YBP to present) drought in northern New Mexico, USA, using diatom valves 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 indirect radiocarbon solar intensity data and were both significantly cross-correlated with solar intensity. Periods of drought aligned with periods of decreased solar intensity during ~1400–1000 and ~600–200 YBP; periods of increased solar activity aligned with periods of increased precipitation during ~1000–600 YBP and ~200 YBP to present day. These results suggest that longer-term drought regimes in northern New Mexico may have been modulated by solar activity.

Key words: diatoms, drought, lake sediments, SiZer, southwestern USA

Introduction

Many regions throughout the world are experiencing unprecedented climate change (Mann and Jones 2003, Smol et al. 2005, Seager et al. 2007, Williams and Jackson 2007). To establish a historical baseline to compare observed and predicted changes, particularly across different biomes and climate regions, researchers have reaffirmed the importance of paleoenvironmental studies. Paleoenvironmental proxies can be used to establish pre-anthropogenic conditions, assess the range of climatic patterns, and calibrate climate change models (Fritz 1996); however, differences in proxy types and extrapolation methods across regions weaken interpretive power because of limitations and ambiguity of results (Woodcock 1992, Betancourt et al. 2002, von Storch et al. 2004, Wahl et al. 2006). Also, when using proxy data, the occurrence of no-analog climates (climates unlike any of today; Williams and Jackson 2007) can confound our

understanding and modeling confidence. Due to shifting baselines, today's climates and subsequent ecological communities may be markedly different from those found in the past and will most likely be different from those in the future (Jackson and Williams 2004, Williams and Jackson 2007). New tools and analyses offer improvements that result in more robust analysis, comparison, and calibration of proxies (Mann et al. 2008).

No-analog communities have the same extant species in different relative compositions than those found today (Williams and Jackson 2007). Because climate change is often multivariate (e.g., temperature, precipitation, insolation) and organism niches are multidimensional (Hutchinson's N-dimensional niche hypervolume; Hutchinson 1957), climate change shifts the proportions of co-occurring species through time (Jackson and Overpeck 2000, Williams and Jackson 2007). In other words, species assemblages are flexible through time as they are

influenced by environmental conditions, and they adjust their niche to utilize previously unrealized aspects of these niches; therefore, climate change could potentially cause stochastic shifts in community composition. Because many paleoclimate proxies are calibrated with modern observations, nondeterministic community changes may reduce the confidence in ecological forecasts (Hobbs et al. 2006, Williams and Jackson 2007). Thus, forecasts based on species composition assessments are often approached with caution until they can be corroborated with other environmental proxies (Fritz 1996, Williams and Jackson 2007).

In addition to no-analog conditions, understanding climate change at small, regional scales is difficult because of the lack of spatial resolution in historical datasets. The historical records used for global climate forecasting tend to be aggregated from select regions while other regions are ignored, resulting in low geographic coverage (Williams et al. 2007). Furthermore, complexities of coupled ocean–atmosphere interactions and continental effects have caused warming in some regions, little warming in others, and highly variable precipitation patterns (Jones et al. 2001). Instrument data prior to AD 1880 (133 YBP) are rare, which necessitates paleoproxy interpretations (Cohen 2003, Smol and Stoermer 2010). Paleoproxies provide the spatial resolution desired for regional analyses (Barry and Chorley 1999, Cohen 2003); however, asynchrony and variation within proxy records are often poorly understood (Woodhouse and Overpeck 1998, Betancourt et al. 2002, Schulz and Paul 2002). When constructing paleoclimate regimes, it is therefore essential to have proxy data from several material sources because each proxy type has its own strengths, weaknesses, and sensitivities (Woodcock 1992, Cohen 2003, von Storch et al. 2004).

Our study focuses on historical drought regimes in the southwestern USA. Droughts have been a prominent landscape feature in this region for at least 3 millennia (Polyak and Asmerom 2001, Cook et al. 2004, Hodell et al. 2005, Rasmussen et al. 2006). Furthermore, anthropogenic forcing is predicted to cause immediate and unprecedented hyperaridity in this region (Seager et al. 2007). Within the suite of precipitation proxies, tree rings have traditionally been one of the most used and understood (Dean and Robinson 1978, D'Arrigo and Jacoby 1991). Because lakes are well-known integrators of climate, diatoms (Bacillariophyta) also have emerged as robust proxies due to their ubiquity and broad-ranging environmental sensitivity (Battarbee 1986, Cohen 2003, Smol and Stoermer 2010). Specifically, considerable evidence has demonstrated that diatoms deposited in lake sediments are reliable indicators of lakewater pH (Whitmore 1989, Weckström et al. 1997, Rosén et al. 2000), lake levels (Barker et al. 1994, Hyvärinen and Alhonen 1994, Heinsalu et al. 2008), and lake salinity (Fritz et al. 1993,

Hodgson et al. 1996, Laird et al. 1998, Pienitz et al. 2000).

We cored the sediments from Santa Fe Lake (New Mexico, southwestern USA) for diatom analysis. Because diatoms respond to many aspects of precipitation and water level dynamics, the sedimentary diatom record from this lake has great potential for reconstructing the relationship between lake conditions, droughts, and wet periods. The objective of this study was to examine whether past drought cycles could be inferred from sedimentary diatom remains and evaluated against an existing tree ring record from the region (Grissino-Mayer 1995, 1996). Additionally, we compared our diatom record with an indirect proxy of solar intensity (Reimer et al. 2004) to consider the potential role of solar forcing on drought.

We investigated this region for 3 reasons. First, the region is highly susceptible to anthropogenic alterations (Rosenberg 1978, Lins and Stakhiv 1999, Seager et al. 2007). Second, the timing and resolution of droughts in the southwestern USA are debated (Betancourt et al. 2002) and more information is needed. Because there are noticeable gaps in diatom records in this region, our record will be of value in supplementing these records and also resolving unanswered questions about drought cycles. Third, we were able to compare our diatom record with independent proxies from this region to aid in our reconstruction with respect to no-analogs.

As part of our research approach, we explored the utility of a newly developed statistical method, known as significance of the zero crossing of the derivative (SiZer; Zhang and Marron 2005, Rondonotti et al. 2007, Sonderegger et al. 2009) to analyze paleodatasets. Long-term time series data, especially biological sources of climate proxies, often have high amounts of covariance (Woodcock 1992) and noise (von Storch et al. 2004), which can dilute actual trends and/or produce type-I errors by creating the appearance of changes when none are statistically present. SiZer is a method developed specifically to address statistical noise and identify significant changes and true modality in time series data. We applied SiZer as a method to elucidate concurrent changes in diatoms, tree rings, and solar intensity. By doing so, we could begin to understand which environmental factors, and their timing, were important at the niche level in driving changes in diatom species assemblage. This information is useful for developing and improving the tools for validating historical interpretations and ecological forecasts.

Study site

Santa Fe Lake (35.7887905N, –105.7780076W) is a closed-basin, cirque, and alpine lake (surface area = 1.9 ha, maximum depth = 7.0 m, 3530 m a.s.l., August pH = 7.4) approximately 28 km northeast of Santa Fe, New Mexico,

USA (Fig. 1). The lake has a small basin (surface area = 15.9 ha; lake covers 12% of the entire basin) completely underlain with Precambrian granite, which contributes to its classification as a highly acid-sensitive lake (hardness = 9–26 mg/L, calcium hardness = 6–27 mg/L, and specific conductance = 16–38 $\mu\text{S}/\text{cm}$; Lynch et al. 1988). The lake is located within the Pecos Wilderness Area of New Mexico, is isolated from 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 current mean annual precipitation in the city of Santa Fe is approximately 348 mm; however, Santa Fe Lake is 1000 m higher than the city and likely experiences cooler temperatures and increased precipitation.

Methods

Sediment core

In August AD 2007 we 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). Within the laboratory, the core was extruded and sectioned into 75 discrete 1 cm samples. Approximately 1 g wet mass was taken from each 1 cm subsample for diatom analyses. The remaining portion of each subsample was dried at 50 °C until a

constant mass was obtained. Once a constant mass was obtained, the subsamples were finely ground with a mortar and pestle. Approximately 1 g dry mass from each 1 cm subsample was combusted at 550 °C for 24 h to determine organic content from loss on ignition (LOI).

Additionally, 6 dried, ground, and uncombusted subsamples from the sedimentary sequence were sent to the National Ocean Sciences Accelerator Mass Spectrometry Facility, Woods Hole, Massachusetts, for reservoir-corrected ^{14}C dating of bulk organic matter (present day = AD 1950; the median calibrated age was determined from the 2-sigma calibration data from INTCAL 98; Stuiver et al. 1998). We used bulk organic matter because our sediment core was devoid of usable twigs, charcoal, leaves, cones, or shells suitable for dating. Also, we elected to only use ^{14}C methodology because the present day calibration of AD 1950 (63 YBP) had the same calibration as the solar intensity data we used in our comparative analysis (Stuiver et al. 1998). Samples were taken from depths of 0, 15, 30, 45, 60, and 74 cm because these depths were at approximately evenly spaced intervals. We dated the top of the sediment core, despite it being post AD 1950, to test for any water chemistry or terrestrial organic matter loading effects on the sediment age and found none. A chronology was constructed by fitting a cubic spline regression to the age-depth profile. Because of the interpolation of estimated dates between each known ^{14}C date, all inferred sediment core dates are noted with the symbol ~ throughout the text. All sediment dates throughout the remainder of this paper are in the form of YBP rather than AD.

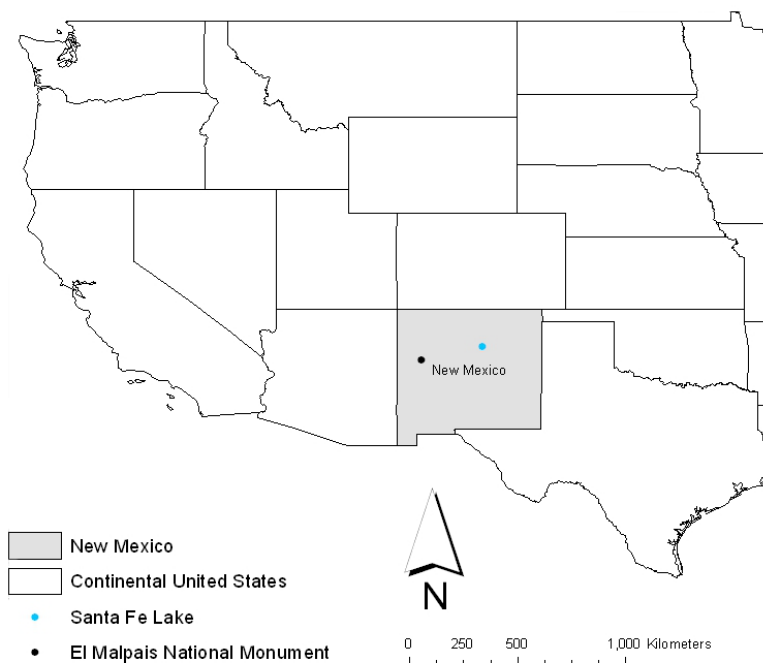


Fig. 1. Location map of Santa Fe Lake with the site of Grissino-Mayer (1995, 1996) tree ring studies in New Mexico, USA.

Diatom enumeration

We prepared each subsample designated for diatom analysis using the 30% H₂O₂ digestion and suspension method of Battarbee (1986). Diatoms were mounted on glass slides with Naphrax and identified by use of a 1000× Zeiss Axioskop phase contrast microscope following the taxonomy of Patrick and Reimer (1966, 1975), Williams and Round (1987), and Wehr and Sheath (2003). All species names and synonyms were updated using the Integrated Taxonomic Information System database (ITIS) and the North American Diatom Ecological database with information current as of 2009. At least 600 frustules per 1 cm sample were counted to determine the relative abundance of each species.

Tree ring and solar intensity records

We downloaded the 2129-year tree ring reconstruction of New Mexico precipitation reported in Grissino-Mayer (1995, 1996) from ftp://ftp.ncdc.noaa.gov/pub/data/paleo/treering/reconstructions/newmexico/malpais_recon.txt. For our statistical and SiZer analyses, we used the yearly raw data; but for graphic purposes, we used a 20-year moving average of the data commonly cited in the literature. This age profile was established from dendrochronology.

In addition, we downloaded the ¹⁴C data reported in Reimer et al. (2004) from <http://www.radiocarbon.org/IntCal04%20files/intcal04.14c> and used these data as an indirect proxy of solar intensity (Beer 2000). More positive ¹⁴C values indicate a cooler, less intense sun and more negative values show a warmer, more intense sun (Beer 2000).

Statistical analyses

In addition to visually assessing all diatom species that had a relative abundance $\geq 5.0\%$ in any one depth sample (exceeded 0.5% in at least 1 of the 75 samples), to make climate inferences, we applied statistical analyses to the diatom species-depth profile matrix. To remove the effects of rare species, any species that comprised $< 0.5\%$ of the relative abundance of any depth profile (never exceeded 0.5% in at least 1 of the 75 samples) was removed from the matrix, which reduced the original 80 species to 78. Next, the relative abundance matrix was normalized using the arcsine-square root transformation (Gotelli and Ellison 2004). Then, to reduce the dimensionality of the diatom community and to identify important individual species, we performed principal components analysis (PCA) on its variance-covariance matrix. We used the variance-covariance matrix because it preserves random noise in the

variables, it maintains 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.

As a test of correspondence, we 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, we deleted tree ring data from AD 1992 to 1951 to match the start dates of diatom PC1 and solar intensity at AD 1950 (¹⁴C present day; 0 YBP). Then, we truncated all data series at 1935 YBP (AD 15) because our sediment core ended at this date. All cross-correlations were run at 1–100 year lags at $\alpha = 0.05$.

Finally, we analyzed the newly created PCA axes, the yearly tree ring raw data (Grissino-Mayer 1995, 1996), and solar activity data (Reimer et al. 2004) with SiZer (a freeware application distributed from www.wagner.com). This method applies a series of smoothing functions based on bandwidths around the data to statistically analyze which data in a time series are trends and which data are noise or are attributable to sampling variation (Zhang and Marron 2005, Rondonotti et al. 2007, Sonderegger et al. 2009). 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 bifurcation in the composition of the data structure that is independent of noise or sampling variability. Once the SiZer analyses were completed, we visually compared regions of significant zero crossing for correspondence in pattern and timing among all of the variables measured (diatom PC1, tree rings, and solar intensity).

Results

Sediment core characteristics

The top sample of the core was ¹⁴C dated as post-present day (present day = AD 1950; 0 YBP \pm 40 years) and thus was considered as AD 1950 (0 YBP) to maintain consistency with the other 5 ¹⁴C dates (Fig. 2). The deepest sample of the core (74 cm) dated to 1902 YBP \pm 40 years. Extrapolation of the spline dates the bottom (75 cm) to be 1935 YBP.

The core was dominated by a nearly homogeneous slurry of gyttja at all depths from the surface to the

bottom. The bulk organic content of the core (Fig. 3) was mostly consistent throughout the core (range 28.4–31.7%), with exceptions from between ~600 and 400 YBP, when there was a reduction in organic matter, and then a rapid increase in organic matter after ~200 YBP (range 24.2–

46.3%). Such trends are not anomalous and were likely the result of compaction and early diagenesis (Dearing 1986, Heinsalu et al. 2008); however, the increase may be the product of anthropogenic nitrogen emissions to the atmosphere.

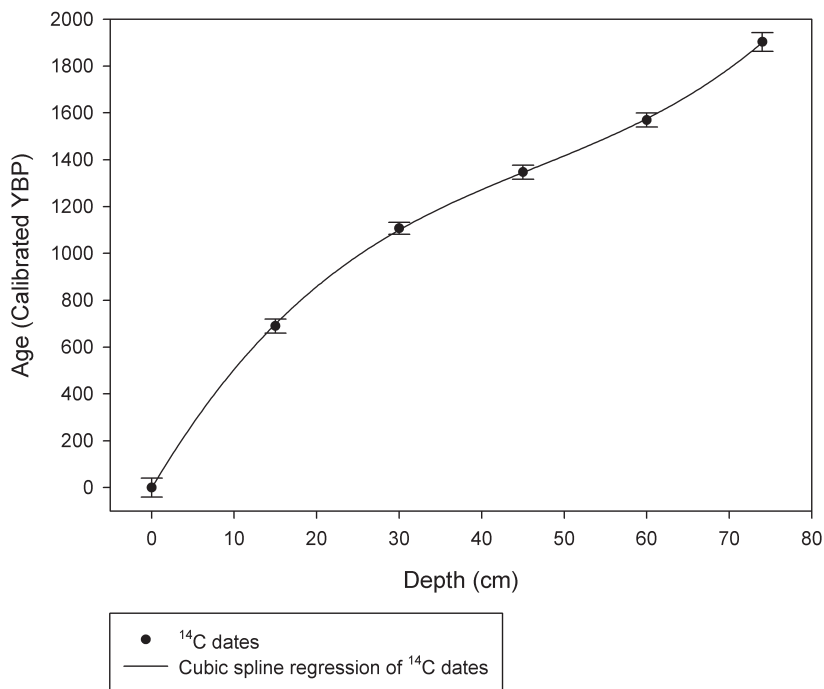


Fig. 2. Age–depth profile for the Santa Fe Lake sediment core based on ¹⁴C analyses; points were best-fit with a cubic spline regression, and error bars are fraction of modern ¹⁴C error.

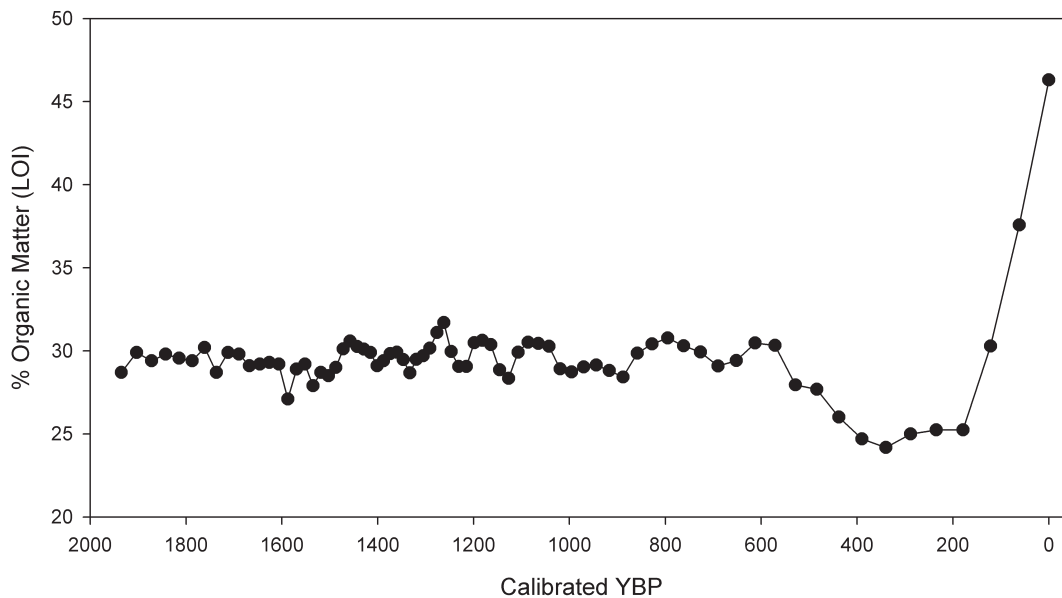


Fig. 3. Organic content–depth profile for the Santa Fe Lake core determined by loss on ignition (LOI).

Diatoms

The diatom community contained 80 species from 32 genera and was plastic throughout the depths of the Santa Fe Lake core. The most abundant 16 species, each with at least 5.0% relative abundance at any point in the core (Fig. 4), contained acidophilic, acid-tolerant, alkaliphilic, circumneutral, and saline-tolerant species. PCA extracted 2 main axes for analyses, which cumulatively accounted for 37% of the total community variance; PC1 accounted for about 24.0% of the variance within the diatom community (Fig. 5), and PC2 accounted for about 13.0% of the variance. When we raised the 0.5% relative abundance inclusion threshold to reduce the species matrix in an attempt to increase the variance extracted, there was no appreciable increase in variance explained. Of the 16 most abundant species, 7 diatoms were strongly associated with PC1 (communalities >0.50) and 3 with PC2. Consequently, we used only PC1 for further analyses.

Species with the most positive loadings and greatest communalities along PC1 included *Aulacoseira distans* var. *alpigena* (Grunow) Simonsen, *Cyclotella meneghiniana* Kützing, *Navicula radiosa* Kützing, and *Synedra tenera* W.Smith (syn. *Fragilaria tenera* [W.Smith] Lange-Bertalot). Ecologically, *N. radiosa* prefers circumneutral water but can tolerate acidic pH levels (Hustedt 1939, Patrick and Reimer 1966, 1975, Charles 1984, 1985). *Aulacoseira distans* var. *alpigena* is an oligotrophic indicator frequently used to show acidic conditions (Marchetto et al. 2004, Štefková 2008, Ognjanova-Rumenova et al. 2011). *Cyclotella meneghiniana* is hyposaline and saline-tolerant (Saros and Fritz 2000) and has been used as an indicator of increases in water salinity (Gasse 1987, Laird et al. 1996, 1998, Leland and Berkas 1998); it tolerates slightly acidic pH levels (Unrein et al. 2010). Additionally, *C. meneghiniana* has been shown to have its greatest relative abundance in shallow lakes (Cumming et al. 1995), and *Synedra tenera* is an acidophilic species (Hustedt 1939, Patrick and Reimer 1966, 1975, Lynch et al. 1988, Charles 1984, 1985).

Conversely, PC1 was negatively loaded by *Planothidium lanceolata* (Brébisson ex Kützing) Lange-Bertalot (syn. *Achnanthes lanceolata* [Brébisson ex Kützing] Grunow), *Staurosira construens* var. *venter* (Ehrenberg) Hamilton, and *Staurosirella pinnata* (Ehrenberg) Williams and Round. These 3 species are small, alkaliphilic, and benthic taxa (Hustedt 1939, Patrick and Reimer 1966, 1975, Charles 1984, 1985, Laing et al. 1999); therefore, as PC1 scores became more positive, the relative abundances of *A. distans* var. *alpigena*, *C. meneghiniana*, *N. radiosa*, and *S. tenera* increased, which suggested the lake water became more acidic and saline. Likewise, their decline

was indicative of waters becoming less saline and acidic (PC1 scores become more negative). As the PC1 scores became more negative, the relative abundances of *P. lanceolata*, *S. construens* var. *venter*, and *S. pinnata* increased, which suggested the lake water became more alkaline; likewise, their decline was indicative of reduced alkalinity (as PC1 scores became more positive). Ultimately, it seems that as a whole, PC1 was capturing diatom community variance associated with changes in water chemistry.

SiZer indicated 4 significant changes in diatom PC1 along this continuum between the family of bandwidths in the $\log_{10}(h) = 1.91$ to 2.37 spectra (Fig. 5, top panel). Between ~1439 and 1000 YBP, diatoms significantly changed to more positive PCA scores (from about -0.4 to +1.3). After this, between ~1000 and 585 YBP, the diatoms significantly changed to more negative PCA scores (about +1.3 to -0.5). Between ~585 and 213 YBP, diatoms again significantly shifted toward more positive PCA scores (about -0.5 to +2.5). Subsequently, between ~213 YBP and present day, the PCA scores become significantly less positive (about +2.5 to +0.4) for the remainder of the series.

Cross-correlations

The paleoprecipitation data from tree rings (Fig. 4 and 5; Grissino-Mayer 1995, 1996) were used in the SiZer analysis, which indicated 6 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. 5). The radiocarbon data from Reimer et al. (2004), a proxy for solar activity, also showed variation through time (Fig. 4 and 5). Our SiZer analyses on the solar activity data showed 4 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. 5).

We used cross-correlation analysis to test the relationships among the tree ring-inferred precipitation patterns, radiocarbon-inferred solar activity, and diatom PC1-inferred lake properties (Fig. 6). First, the tree ring data of Grissino-Mayer (1995, 1996) and diatom PC1 were significantly correlated at zero lag ($r = -0.15$, $p < 0.002$). The strongest correlations were at -63 and +15 years ($r = -0.17$, $p < 0.001$, respectively), implying that as inferred precipitation increased, diatom PC1 became more negative. Also, the ^{14}C data of Reimer et al. (2004) and diatom PC1 were significantly correlated at zero lag ($r = 0.78$, $p < 0.001$). The strongest correlation was at -24 years ($r = 0.79$, $p < 0.001$), suggesting that solar activity had a near-zero lag effect on the diatom community in Santa Fe Lake; as solar intensity increased, diatom PC1 became more negative. Finally, the relationship between

tree rings and solar activity was significantly correlated at zero lag, which was also the strongest correlation in the comparison ($r = -0.15, p < 0.001$), suggesting that solar

intensity may be related to inferred precipitation; as solar intensity increased, precipitation may have concomitantly increased with zero lag.

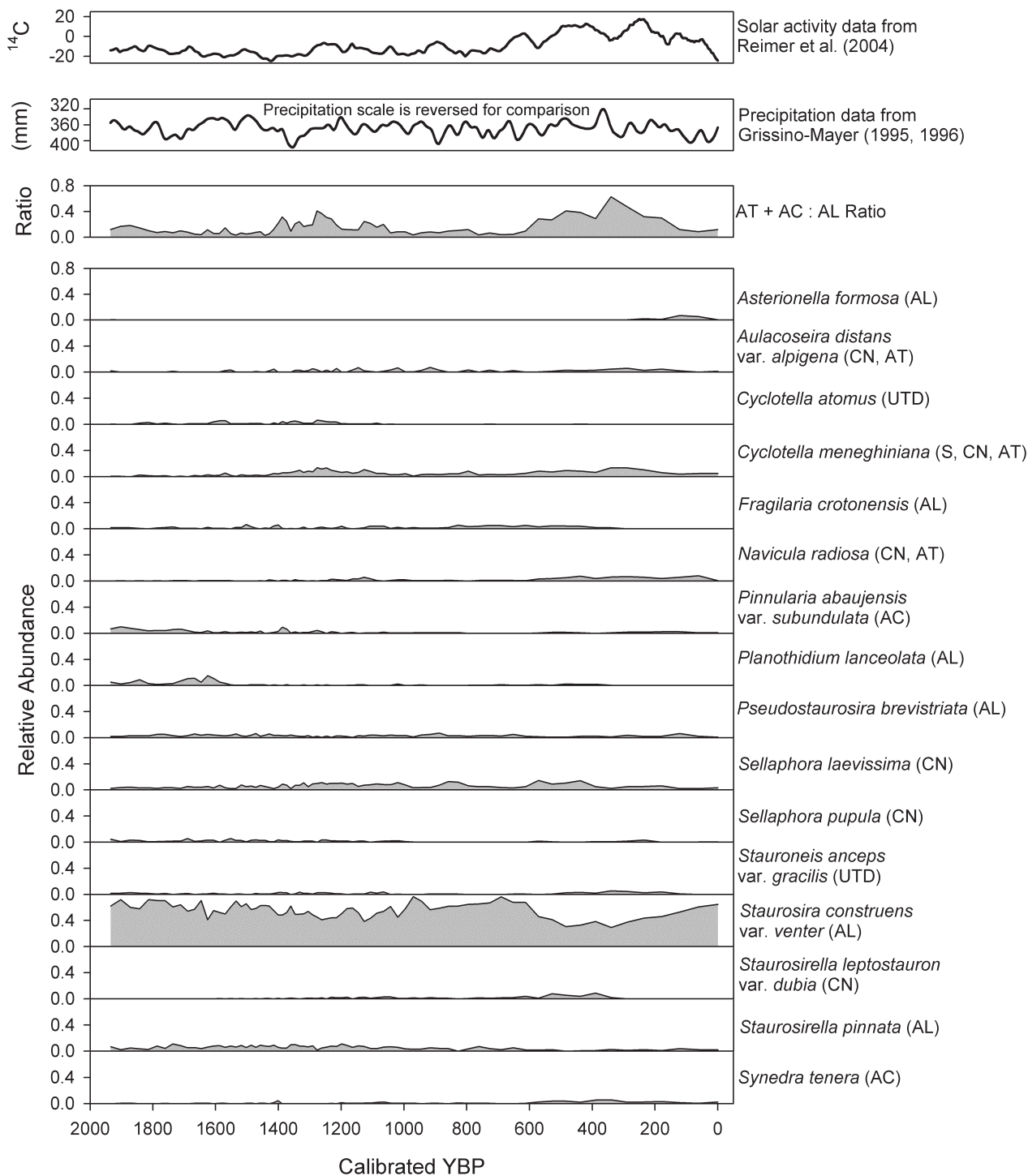


Fig. 4. Diatom stratigraphy of Santa Fe Lake for the most common 16 species plotted along with the tree ring record (20 year moving average) and solar activity record. The precipitation scale on the tree rings has been reversed to aid in visualization. AT = acid-tolerant, AC = acidophilic, AL = alkaliphilic, CN = circumneutral, S = saline-tolerant, and UTD = undetermined.

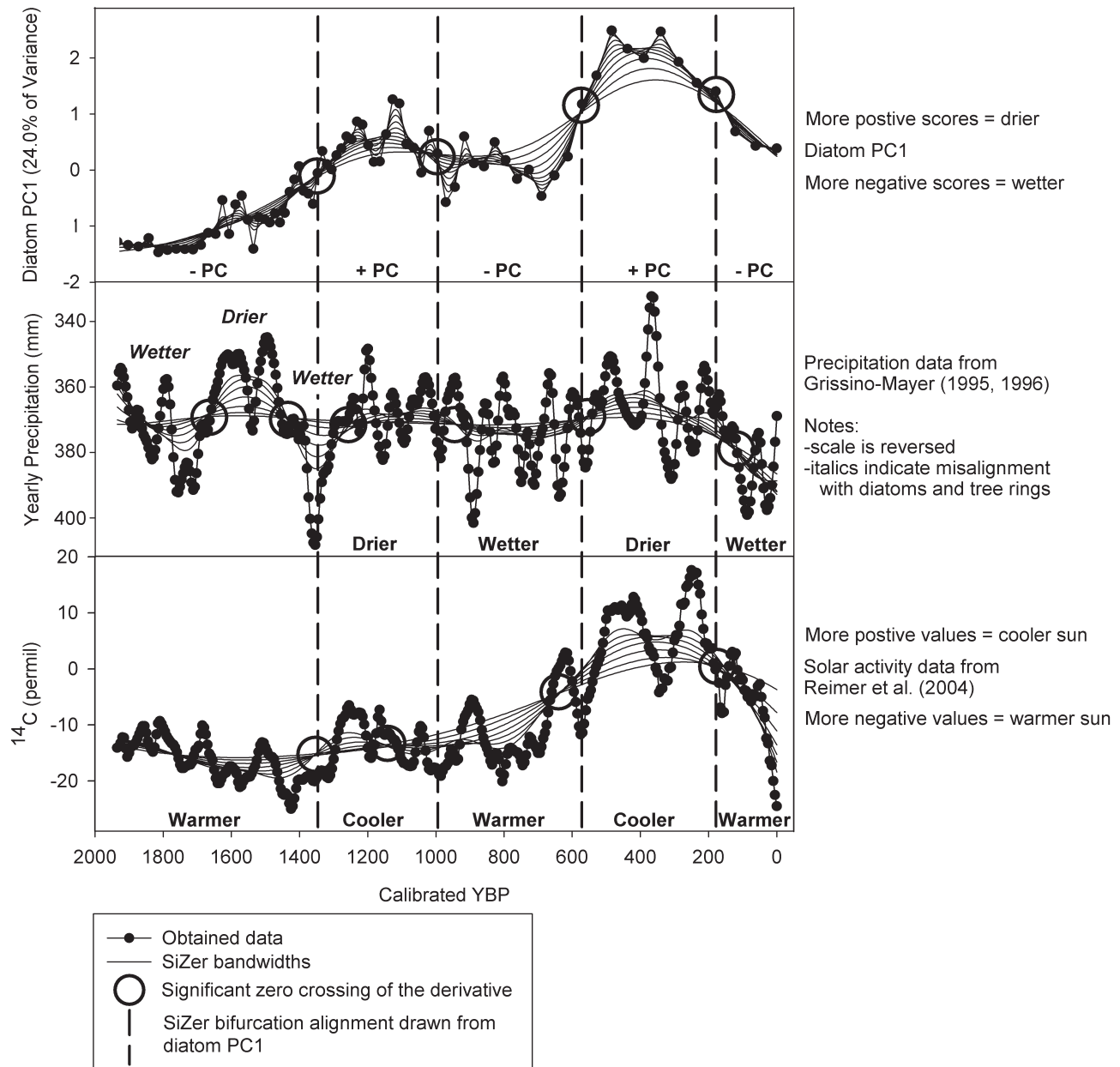


Fig. 5. SiZer analyses of diatom PC1, tree rings, and solar intensity. Solid circles are obtained data and the solid lines are the SiZer bandwidths. The tree ring plot shows the 20-year moving average of precipitation and the SiZer bandwidths around yearly raw data. Open circles represent significant zero crossings of the derivatives. The vertical dashed lines are to aid in visual alignment of diatom PC1 bifurcation points with the other 2 series. The precipitation scale on the tree rings has been reversed to aid visualization. The italic print on the tree ring plot represents misalignments with diatom PC1 and solar activity.

Discussion

Climate change has increased the need for paleoenvironmental climate studies and tool development using multiple proxies to address concerns over species assemblage interpretations, proxy sensitivity, spatial resolution, and geographic coverage (Fritz 1996, von

Storch et al. 2004, Wahl et al. 2006, Williams and Jackson 2007, Mann et al. 2008). The main objective of our study was to generate a diatom-inferred, long-term drought record for the southwestern USA and compare it to the independent proxy record of precipitation. We inferred long-term drought intervals of about 400 years spanning ~1400–1000 and ~600–200 YBP. This trend coincided

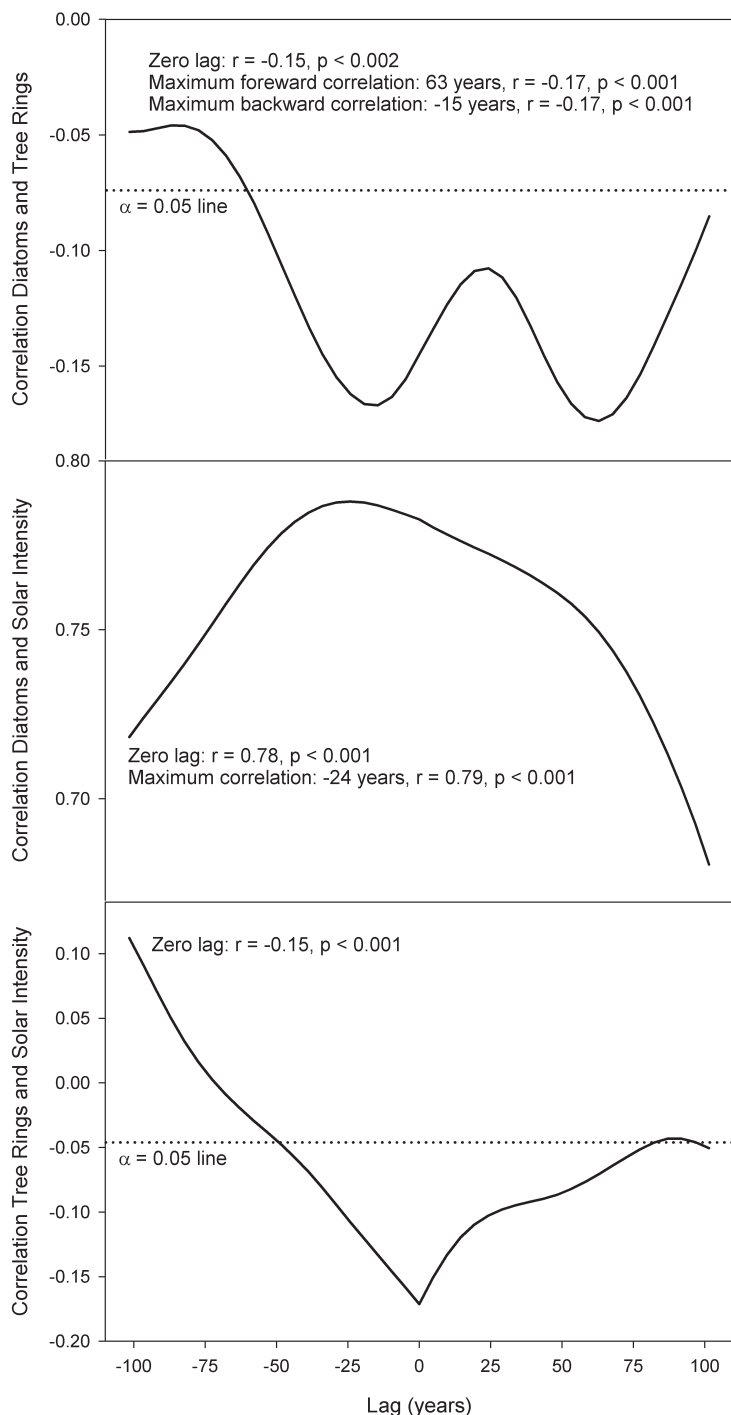


Fig. 6. Cross-correlations among diatom PC1, tree rings, and solar intensity.

with radiocarbon proxies of solar intensity and suggested that solar intensity determined the drought regime. Thus, this study provides much needed regional-scale information on climate change by using a multi-proxy approach that also includes the use of statistical tools (SiZer) previously not applied to paleoenvironmental

research. This suite of approaches and new tools serve as a model for other regional-scale investigations.

Interpretations of species assemblage

Climate change can cause stochastic reorganization of species assemblages due to niche shifts; in such cases, changes in species composition can be used to infer environmental changes and niche ecology (Williams and Jackson 2007). Changes in Santa Fe Lake diatoms allowed us to make 2 ecological conclusions about how lake conditions changed through time.

First, reduced lake levels and increased salinity are linked. Saline-tolerant and hyposaline species of diatoms commonly have been used to infer differences in salinity caused by changes in lake levels (Gasse 1987, Hodgson et al. 1996, Pienitz et al. 2000). Germane to Santa Fe Lake, Laird et al. (1996, 1998) utilized hyposaline *Cyclotella meneghiniana* (Saros and Fritz 2000) as part of the species assemblage to infer periods of drought, reduced lake levels, and increased salinity in Moon Lake, North Dakota, USA. During their inferred periods of prolonged drought, *C. meneghiniana* reached relative abundances >15–20%. Likewise, Fritz et al. (1994) and Leland and Berkas (1998) interpreted *C. meneghiniana* as a water level and salinity indicator in Devils Lake, North Dakota. Cumming et al. (1995) found in Canada that *C. meneghiniana* was most abundant (20–30% relative abundance) in lakes shallower than 4.3 m deep. Furthermore, in a comparative study of 40 Spanish reservoirs, Negro and De Hoyos (2005) showed that *C. meneghiniana* was strongly associated with elevated water mineral content and conductivity. In Santa Fe Lake, *C. meneghiniana* increased in relative abundance (maximum about 15%) between ~1400–1000 and ~600–200 YBP. Because *C. meneghiniana* has a flexible niche, inferring salinity changes based on one species may be elusive. Considering Gasse (1987) and Laird et al. (1998) both classified *C. meneghiniana* as a facultative planktonic species (in Niger and USA, respectively), however, and both Cumming et al. (1995) and Leland and Berkas (1998) noted increases as water levels declined, a strong argument linking increases in *C. meneghiniana* to decreases in lake levels can be made for shallow Santa Fe Lake regardless of interpretations of salinity. Conversely,

between ~1000–600 YBP and ~200 YBP to present, the proportion of this species decreased, suggesting lake levels likely increased and salinity may have decreased.

Second, reduced lake levels and increased acidity are linked. Diatoms have routinely been used as robust indicators of inferred changes in lake pH (Whitmore 1989, Round 1990, Psenner and Schmidt 1992, Weckström et al. 1997, Rosén et al. 2000). Changes in alkalinity can come from a variety of mechanisms, but research has indicated that droughts and lake level reductions can induce acidification in waters, particularly those that are highly acid-sensitive with low calcium hardness and acid-neutralizing capacity (ANC; Brakke 1981, Bayley et al. 1992, Arnott et al. 2001, Faulkenham et al. 2003). The premise of this phenomenon is that shallow lakes with low ANC values, particularly with small basins, have the majority of their alkalinity produced internally through biological reduction of iron, sulfate, and nitrate (Schindler 1988). Drops in lake levels may expose the littoral zone to the atmosphere, which could hinder reductive pathways that produce alkalinity (Schindler and Turner 1982, Schindler 1988). Likewise, drops in water levels and/or the oxidation of these compounds (chemically reduced forms of iron, sulfur, and nitrogen) will increase proton concentration (Brakke 1981, Bayley et al. 1992, Schlesinger 1997). Santa Fe Lake has a small basin (15.9 ha) completely underlain with Precambrian granite (Lynch et al. 1988). The lake has a shallow (<1 m deep) and narrow littoral zone (extending 1–5 m from shore) before steep drop-offs into the limnetic zone. Moreover, the current calcium hardness (6–27 mg/L) and ANC values 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).

During periods of increased salinity (~1000–600 YBP and ~200 YBP) in Santa Fe Lake, changes in the acid-tolerant + acidophilic:alkaliphilic ratio of diatoms corresponded (Fig. 4), providing evidence for drought-induced acidification. Specifically, acidophilic *Synedra tenera* and acid-tolerant *Aulacoseira distans* var. *alpigena* and *Navicula radiosia* increased during periods when lake levels declined. *Cyclotella meneghiniana* often prefers circumneutral and slightly alkaline water, but lake and mesocosm evidence shows it survives in acidic waters (Blouin 1989, Unrein et al. 2010), further suggesting it was a drought species in Santa Fe Lake. Concomitantly, alkaliphilic species *Planothidium lanceolata*, *Staurosira construens* var. *venter*, and *Staurosirella pinnata* decreased. Interestingly, the ratio of planktonic:periphytic species increased during periods of drought, probably due to the decrease in the dominant benthic species *S. construens* var. *venter* during periods of increased acidity. Changes in

water chemistry were likely more influential to diatom life form changes than only planktonic and benthic habitat formation.

Corroboration of species assemblage

Paleoenvironmental studies, especially those using species composition data, are improved when using multiple proxies (Fritz 1996, Williams and Jackson 2007). We explored the relationships between community-level diatom changes (PC1; Fig. 5) with tree ring records of precipitation (Grissino-Mayer 1995, 1996) and radiocarbon proxies of solar intensity (Reimer et al. 2004). As diatom PC1 scores became more positive, the relative abundances of diatom species tolerant of acidic pH, increased turbidity, and increased salinity became greater. These trends suggested long-term drought. Conversely, as PC1 scores became more negative, diatoms species associated with increased alkalinity became more abundant, which suggested nondrought conditions.

The tree ring record was significantly cross-correlated inversely with diatom PC1, showing that as precipitation increased, alkalinity increased and salinity decreased. While there was some lag in the cross-correlations between tree rings and diatom PC1, this may be due to differences in dating methods (dendrology vs. ^{14}C). The maximum error rate in our ^{14}C radio-dates was ± 40 years. When considering the time between the maximum correlation was 78 years (lag at 15 and -63 years, $r = -0.17$, $p < 0.001$, respectively) and the ^{14}C error rate ± 40 years, there is ample support suggesting diatoms and tree rings captured the same precipitation variance within a ± 40 year window (best case scenario no lag; worst case scenario 103 year lag).

The solar activity record was also significantly cross-correlated with both diatoms and the tree ring record, each at zero lag, respectively. This 3-way statistical metric was used to assess possible transitive relationships between solar intensity, precipitation, and diatom dynamics. The prevailing trend was that as solar intensity decreased, tree rings indicated decreased precipitation and diatoms suggested lower lake levels. While correlation cannot prove causation, this significant 3-way correlation between solar intensity, diatoms, and tree rings implied that these independent proxies could be linked and suggested that decreased solar intensity may have been a driving force in causing prolonged droughts in this climatic region.

Additional insights about emerging methods

Our study entailed 3 proxy record types, each with different sensitivities and temporal resolutions, providing an excellent opportunity to assess new ways of interpreting and corroborating multiple proxies. Tree ring records

of precipitation and isotopic fractionation representative of solar intensity often have annual resolution (D'Arrigo and Jacoby 1991, Reimer et al. 2004), but sedimentary diatoms work best as longer-term integrated responses (Battarbee 1986, Cohen 2003). Furthermore, according to statistical theory, most time series data exhibit a low frequency noise spectrum that increases the overall variance with length of time (Gotelli and Ellison 2004). In other words, type-I errors increase proportionally with the length of the time series. This posed a challenge during our analyses because aligning individual peaks and nadirs among 3 proxies with different resolutions and sensitivities may be difficult and often subjective. Moreover, it may lead to falsely inferring cycle length, especially when using shorter-term time intervals to reconstruct longer-term climate cycles.

We selected SiZer to address potential shortcomings of species assemblage interpretations and no-analog communities because they could compare 3 independent proxy records. Our analyses (Fig. 5) emphasized multiple bandwidths over the weight of any single time interval to reduce noise and permit statistical identification of bifurcation points when proxies changed from one regime to another. This resulted in an objective analysis of noisy data that allowed us to establish long-term cyclical concordance that may have otherwise not been possible. As a whole, diatoms, tree rings, and solar intensity showed concordance with respect to their bandwidths. We expected some differences among them because of their different aging techniques and sensitivities, and although some asynchrony was found between the proxies (cross-correlation lags; also see italics in middle panel, Fig. 5), these regimes had mostly corresponding significant zero crossings (large open circles) along approximate 400 year intervals. These cycles were similar in length to other long-term drought regimes reported in North America (Cook et al. 1996, Laird et al. 1998, Yu and Ito 1999, Hodell et al. 2001). In conclusion, our analyses demonstrating proxy concordance are encouraging, especially the comparison of longer-term integrated responses of diatoms with shorter-term proxies, and offer new insight into the long-term climatic variability in the southwestern USA. This approach could also be useful in integrating multiple proxies over larger spatial scales.

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